

NAL PROPOSAL No. 0092

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A NEUTRINO EXPERIMENT IN THE NAL 30m³ BUBBLE CHAMBER
USING "MONOENERGETIC" NEUTRINOS

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August 26, 1970

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Abstract

We propose to use the NAL 30m³ Bubble chamber to study $\nu(\bar{\nu})$ interactions. The scheme proposed in NAL Proposal #21 to obtain incident neutrinos with known momentum and angle is employed. We will cover the energy region 30-80 GeV using pion neutrinos and simultaneously the region 80-200 GeV with kaon neutrinos.

The experiment is capable of the following physics:

I) Studying in an unambiguous and systematic free way the behavior of σ_{Total} vs. E_{ν} from 30-200 GeV by using hydrogen in the Bubble Chamber.

II) Making meaningful and clean comparisons of $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ cross-sections by comparing hydrogen and deuterium and reversing the polarity of the hadron beam.

III) Studying details of the inelastic scattering $\frac{d^2\sigma}{dq^2 dv}$ both with good statistics in neon, and with poorer statistics in hydrogen, which is free of A-dependent effects. Detailed information on the final hadronic state will be obtained.

IV) If the W-Boson exists and can be produced, information on its decay modes will be obtained.

We request 250K expansions, each, for the chamber filled with hydrogen, deuterium, and neon. This will enable us to obtain $\sim 5\%$ measurements on the various total cross-sections and about 100K inelastic events in neon.

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I. Physics Justification

A) Introduction

We propose to investigate neutrino physics in the energy region 30-200 GeV using the NAL 30m³ bubble chamber. Recently, due to muon shielding problems, it has been proposed to position the bubble chamber \sim 1000 meters downstream of the decay tunnel. This allows the use of an earth shield for the chamber. Placing the bubble chamber far downstream of the decay tunnel has opened up the possibility of using a "monoenergetic" neutrino beam.

The technique described in NAL Proposal #21 is to be used to define the incident momentum and angle of the neutrinos. The largest source of error in this method comes from the parallax at the apparatus, introduced by the long decay tunnel. By placing the bubble chamber 1000 meters downstream this error has been minimized. In this proposal, in contrast to NAL #21, we emphasize the use of both pion neutrinos and kaon neutrinos. The pion neutrinos give larger event rates; however, the energy of the incident neutrino is lower and resolution poorer.

Much of the physics for $E_\nu > 30$ GeV in the bubble chamber cannot be done by simply filling the chamber with hydrogen or deuterium. Extra information must be obtained and various possibilities have been proposed (plates in the chamber, hydrogen-neon mixtures, or external hybrid equipment). Using a ν beam of known energy reduces the reliance on external information to resolving a simple ambiguity. Other advantages of a narrow band beam include simple monitoring of the flux and much smaller systematic errors.

Although some of the physics goals overlap the counter experiments, we stress below important questions which will not be easily answered in the counter experiments. These goals for different chamber fillings include:

- I) Hydrogen exposure: σ_T vs. E_ν can be measured on protons in a way free of systematic errors. For each event, details of the interaction including the behavior of the hadronic system can be studied. Since event rates are low for counter or bubble chamber experiments in hydrogen, it seems reasonable to obtain as much information as possible about each event.
- II) Deuterium exposure: By using neutrinos and antineutrinos, a clean comparison of $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ can be obtained.
- III) Neon exposure: A large number of inelastic events will be obtained with the advantages of a bubble chamber. For example, there is a uniform solid angle acceptance, and the ability to see the vertex and study details of the interaction. If the W exists and can be produced, details of the decay modes will be learned.

Below are brief discussions of the physics of these measurements.

B) σ_T vs. E_ν on Hydrogen

Following Bjorken and Paschos⁽¹⁾ the cross-sections for $\nu + p \rightarrow \mu^- + \text{hadrons}$ can be written in terms of form factors W_1 , W_2 , and W_3

$$\frac{d^2\sigma}{dq^2 dv} = \frac{E-\nu}{E} \frac{G^2}{2\pi} \cos^2 \frac{\theta}{2} \left[W_2(q^2, \nu) + 2 \tan^2 \frac{\theta}{2} \left(W_1(q^2, \nu) + \frac{2 E-\nu}{2M} W_3(q^2, \nu) \right) \right] \quad (1)$$

Bjorken and Paschos show that integrating over the differential cross-section and assuming that $W_2(q^2, \nu)$ is scale invariant (i.e., W_2 is function only of $\frac{\nu}{q^2}$) leads to a linearly rising cross-section.

Experiments at CERN⁽²⁾ using a heavy liquid bubble chamber measured the total cross-section up to 12 GeV, which are shown in Fig. 1. A linear fit to the events with $E_\nu > 2$ GeV gives

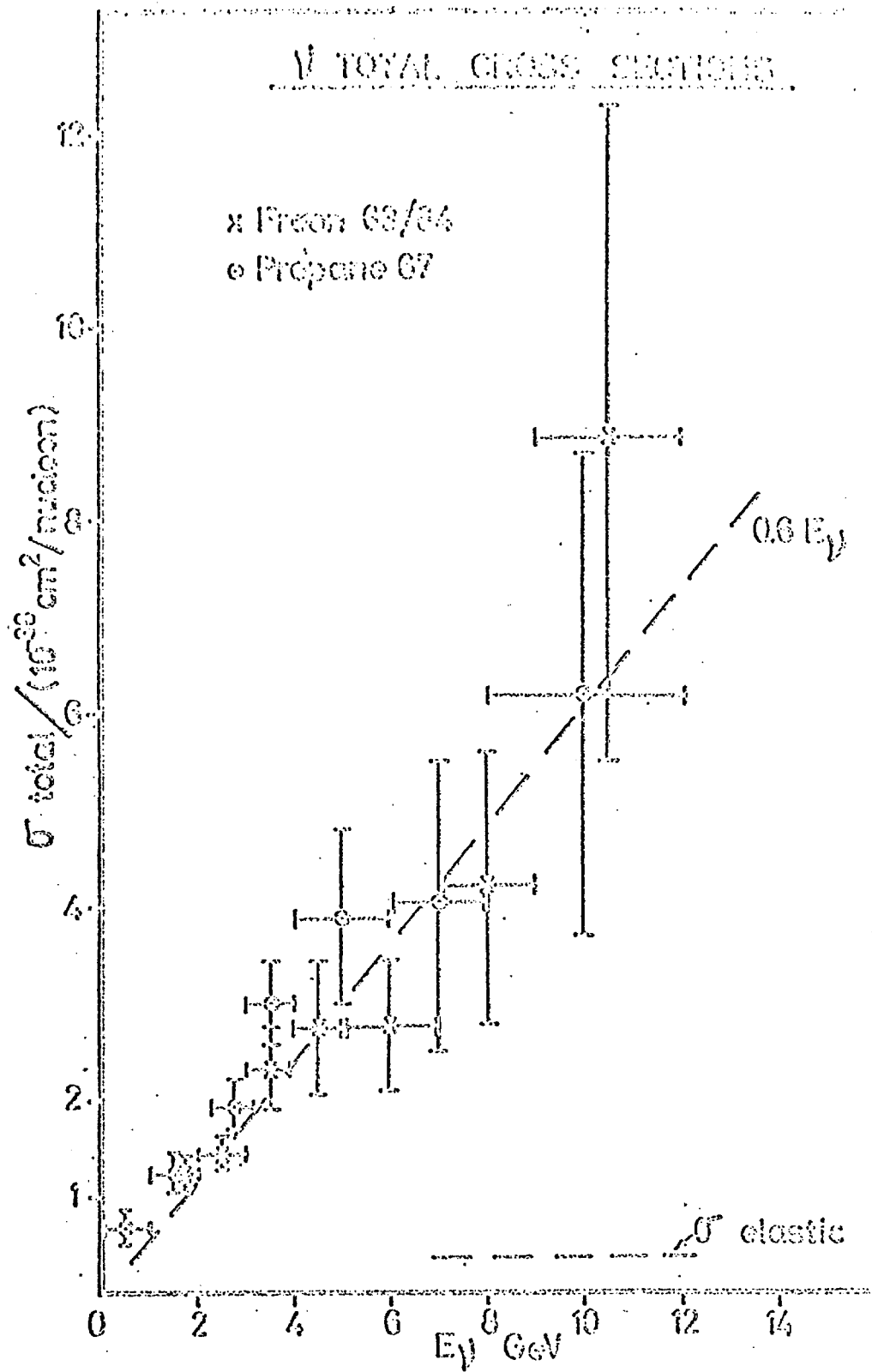


Figure 1

$$\sigma_T = (0.51 \pm 0.13) \frac{G^2}{\pi} ME/\text{nucleon}$$

where the errors are statistical only. As one goes to NAL energies it is important to determine whether σ_T continues to rise linearly.

A turnover in the rising cross-section could be caused by a W-Boson. For example, if the W exists it has a propagator term and $G \rightarrow \frac{G}{1 + q^2/M_W^2}$ in Formula (1). This term damps $\frac{d\sigma}{dq^2}$ at high q^2 and therefore will affect the total cross-section. Figure 2 shows the effect of this propagator on the total cross-section as a function of S/M_W^2 where $S = 2 M_p E_\nu$.

A turnover might also result from a breakdown of scale invariance which would reflect on the basic hadronic structure.

A measurement of the total cross-section is not easy:

In wide band beams, the following problems arise. Preliminary to any neutrino measurements, the hadron flux must be measured accurately at all energies and production angles from the same target that is used for the neutrino beam. At CERN, this measurement was ultimately done by putting the target in the bubble chamber⁽³⁾. The hadron flux is then folded into the acceptance of the focussing system to be used and one obtains the predicted neutrino flux. The resulting neutrino flux curves are expected to fall rapidly with energy. A small systematic error in energy for observed neutrino events creates a rather large flux, and hence cross-section, error. The narrow band beam nicely eliminates these problems. Also monitoring the beam becomes both simpler and more direct.

A second serious difficulty which exists is the use of $A \gg 1$ targets. The A-dependence of the cross-section for neutrino scattering is completely unknown. Experiments show that the total photon cross-section on nuclei is prop-

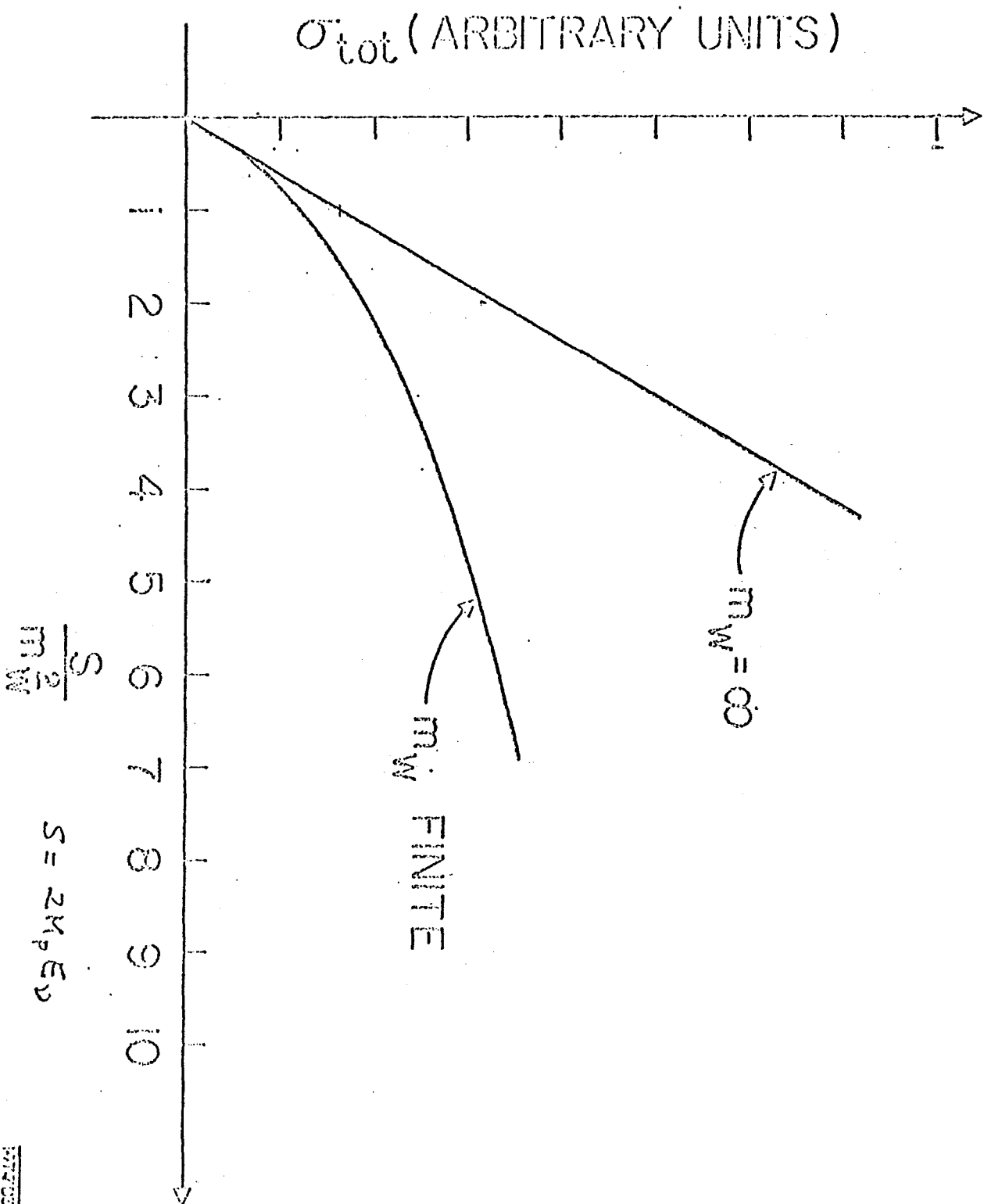


Fig. 2

portional to $\sim A^9$ at 20 GeV⁽⁴⁾. Adler⁽⁵⁾, using PCAC, has predicted a differential cross-section at zero degrees should be proportional to $A^{2/3}$. However, Lovseth and Froyland⁽⁶⁾, using a different version of PCAC, get a cross-section proportional to A . Attempts have been made at CERN⁽⁷⁾ to measure the A -dependence at low energies but the results are rather inconclusive. In view of all this it seems very important to do the total cross-section on hydrogen to obtain unambiguous results.

We propose to obtain this energy dependence on hydrogen and with a momentum defined beam. We will be able to obtain $\sim 5\%$ measurements at 30, 50, and 80 GeV with $\sim 50K$, 25K, and 50K expansions respectively, and simultaneously with kaon neutrinos $\sim 10\%$ measurements at ~ 80 , 125, and 200 GeV.

C) Comparison of $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ Using Hydrogen and Deuterium

Reversing the polarity of the hadron beam negative pions are selected and thereby make a beam of antineutrinos. It should be noted that the unique sign selection in our hadron beam makes the ν contamination in the $\bar{\nu}$ beam negligible and vice versa. Filling the chamber with deuterium and hydrogen and reversing the polarity of the beam enables us to measure $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ at the same incident energy with little systematic error.

A variety of predictions for these ratios and certain sum rules have been obtained from different models of highly inelastic neutrino scattering. For example, parton models⁽⁸⁾ predict

$$\sigma_{\nu} > \sigma_{\bar{\nu}}$$

and

$$\sigma_{\nu p} + \sigma_{\nu n} + \sigma_{\bar{\nu} p} + \sigma_{\bar{\nu} n} \leq 1.72 \frac{G_{ME}^2}{\pi}$$

Drell's field theory parton model⁽⁹⁾ for the region $\omega = \frac{2M_p v}{q^2} \gg 1$ predicts

$$\frac{(d\sigma_{\bar{\nu}}/d\omega)}{(d\sigma_{\nu}/d\omega)} = \frac{1}{3} \text{ for } \omega \gg 1.$$

In contrast diffraction models⁽¹⁰⁾ predict $\sigma_{\nu p} = \sigma_{\nu n} = \sigma_{\bar{\nu} p} = \sigma_{\bar{\nu} n}$ in the region where the models are valid. If the leading trajectories continue to dominate for $\omega \gg 1$, νW_3 is scale invariant. This leads to the result $\frac{(d\sigma_{\bar{\nu}}/d\omega)}{(d\sigma_{\nu}/d\omega)} = 1$ for $\omega \gg 1$.

Harari's⁽¹¹⁾ model, where only the Pomeron contributions are scale invariant and $\nu W_3 \rightarrow 0$ for q^2 large, predicts $\sigma_{\nu} = \sigma_{\bar{\nu}}$ over most of the physical region.

It is apparent that information on the relations between these cross-sections is very important in determining the nature of the basic hadronic structure. Unraveling these cross-sections in the counter-spark chamber experiments is very difficult since it is hard to distinguish an A-dependent effect from a difference in scattering off neutrons and protons. Using hydrogen and deuterium as targets is ideal for making unambiguous measurements.

D) Deep Inelastic Scattering

Information on the distribution of events as a function of q^2 and ν will result from the hydrogen measurements. Although this sample will only consist of ~ 1 -2K events it will be valuable since it is free of all A-dependent effects and will have very good resolution in q^2 and ν . Details about the final hadron state can be studied, for example, the multiplicity as a function of q^2 and ν and momentum and angular distributions of the pions, etc.

The exposure in neon will present a sample of events with all the advantages of the bubble chamber and good statistics (~ 100 K events). Acceptance over

q^2 , ν will be uniform, resolution good, and details about each event available. Questions about whether the cross-section goes to zero or remains finite at $\omega \gg 1$ can be investigated (within the limitations of A-dependent effects).

E) W-decay Modes

If the W-Boson exists and can be produced at $E_\nu \approx 80$ GeV, details of the decay modes could be determined in neon. (A 5 GeV W-Boson would give $\sim 10K$ events into all decay modes.) Detection of $W \rightarrow e\nu$ would be very clean in the bubble chamber and information on the hadronic decays could be determined. The very fundamental question of the coupling of the weak interaction currents to hadronic systems can be investigated by measuring the branching ratios of the decaying boson to hadrons.

F) Conservation of Leptons

Using the two neutrino hypothesis we define a muon number

$$N_\mu = N_{\mu^-} + N_{\nu_\mu} - N_{\mu^+} - N_{\bar{\nu}_\mu}$$

Conservation of leptons can be tested by measuring $\frac{\nu + N \rightarrow \mu^- + \text{hadrons}}{\nu + N \rightarrow \mu^+ + \text{hadrons}}$. This ratio can be measured with great accuracy in this experiment, where the energy is high and π -decay backgrounds from hadrons in the reaction are small and where $\bar{\nu}$ beam contamination is very small.

The two neutrino hypothesis itself can be sensitively tested at very different energies from the original experiments.

If there were only one kind of neutrino $\nu_e = \nu_\mu$ then the reactions

$$\nu + N \rightarrow \mu^- + \text{hadrons}$$

$$\nu + N \rightarrow e^- + \text{hadrons}$$

would be equal. Since $\nu_\mu \neq \nu_e$ and the neutrinos are mainly π -decays, the first reaction predominates. A small limit on this ratio can be made in the neon exposure.

G). Neutrino-Lepton Scattering

The single example thus far observed of a purely leptonic interaction is $\mu \rightarrow e + \nu + \bar{\nu}$. Such interactions are the cleanest means of investigating the current-current hypothesis and the detailed form of the lepton current.

A very general form for the hamiltonian⁽¹²⁾ for this process is

$$H = \sum_i (\bar{e}(C_i + C'_i \gamma_5) \Gamma_i \mu) (\bar{\nu}_\mu \Gamma_i \nu_e) + h. c. \quad (1)$$

where the sum extends over the various types of coupling (S,V,T,A,P).

Present experimental evidence⁽¹³⁾ is such that admixtures of scalar (pseudo-scalar) and tensor amounting to 30% of the vector-axial vector part are possible. Moreover, it has been shown⁽¹²⁾ that, even if all the decay parameters from μ decay were measured to arbitrary precision and found to agree with the predictions of V-A, in fact the hamiltonian would only be restricted to the form $V-\lambda A$, where λ could be measured in μ -decay only by observing decay neutrinos. It is possible⁽¹⁴⁾ to remove this uncertainty by measuring the angular distribution for the reaction

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e. \quad (2)$$

We estimate that we will obtain approximately 300 events of the purely leptonic process (2) in our neon exposure. Figure (3) shows the angular distribution expected for various assumptions concerning λ .

Figure 3.

$$H = \frac{G}{\sqrt{2}} \bar{e}(1-\gamma_5)\gamma_\lambda \mu \bar{\nu}_\mu \gamma_\lambda (1-\lambda\gamma_5)\nu_e$$

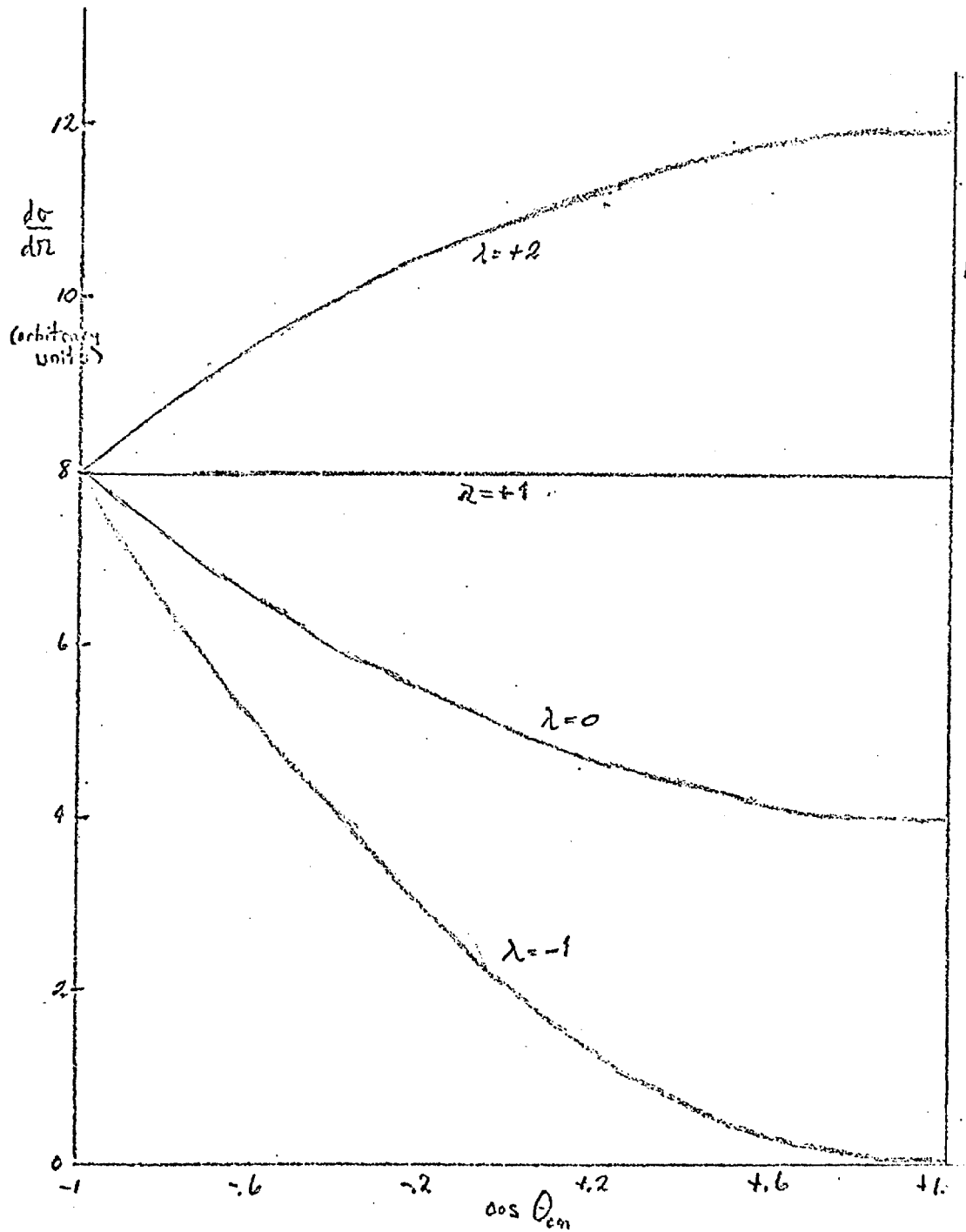


FIGURE 3
Angular Distribution
for
 $\nu_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$
for various values
of $\lambda \equiv g_A/g_V$

V-A theory
for $\lambda = +1$.

This process presents a formidable problem of background separation, since the background from inelastic scattering from the nucleus is expected to be about 300 times as large. The handles which we can bring to bear are:

(1) The observation of only a μ^- coming from the vertex. If we assume that only inelastic events with $\nu \lesssim 330$ MeV will produce no observable charged prongs, this will reduce the background ($E_\nu = 50$ GeV) by a factor of 150.

(2) The lack of conservation of visible energy for the process (2) over most of the range of muon energies.

(3) Two-body kinematics: θ_μ and P_μ on the outgoing μ predict the incident neutrino energy which we have independently measured.

It should be mentioned that events of the type $\nu_\mu + e^- \rightarrow e^- + \nu_\mu$ would also be visible in this experiment. Such events would be evidence for neutral lepton currents.

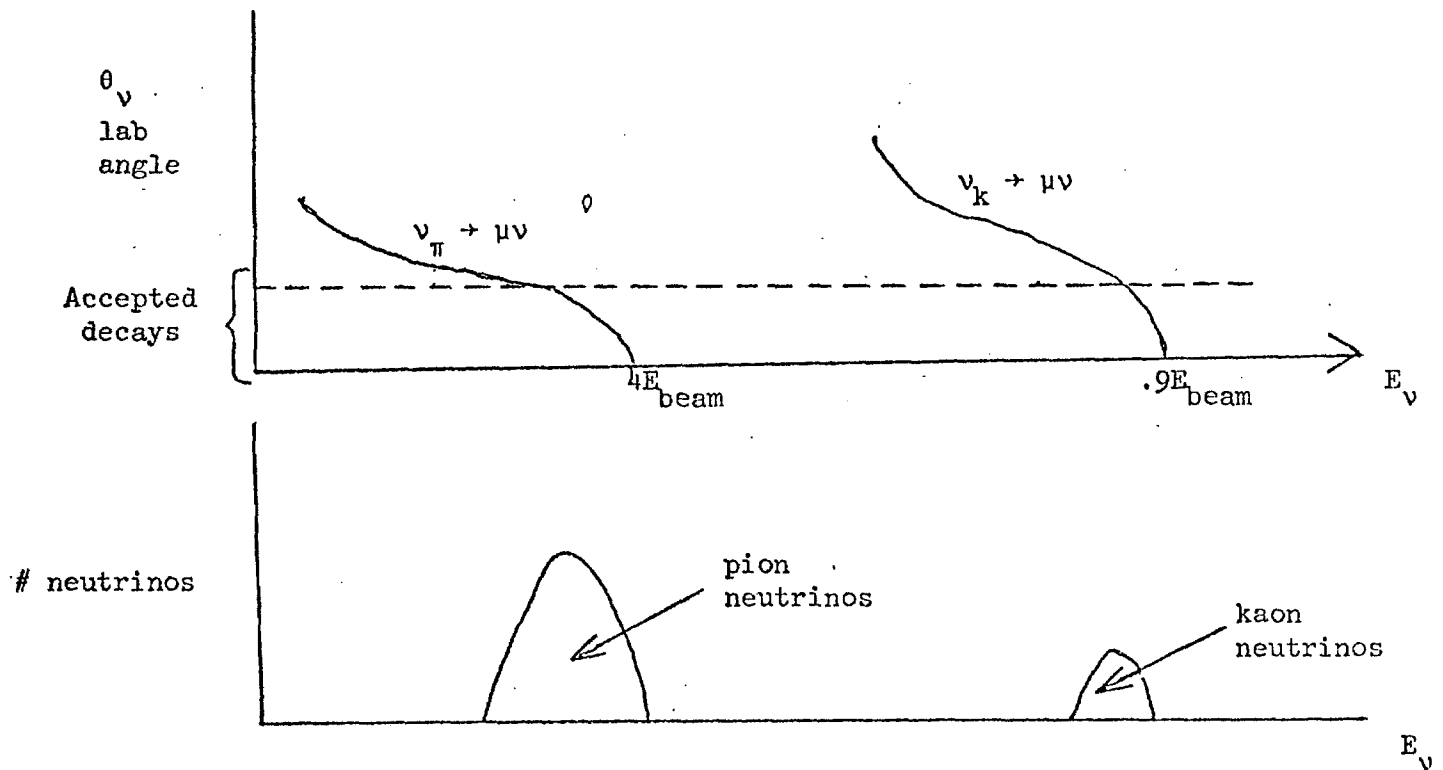
II) Experimental Method

A) Introduction

The method used for obtaining the neutrino beam is similar to NAL #21. We briefly review the method.

In the target box a simple beam transport system which selects hadrons with $\sim \pm 5\%$ momentum bite, forms a parallel beam and sends it down the decay tunnel. Because of the narrow momentum acceptance this hadron beam is both smaller in transverse dimensions and angular divergence than a wide band system.

The pions and kaons that decay in the beam tunnel yield neutrinos whose energy is correlated with their laboratory angle.



If the experimental apparatus can be placed so that θ_ν is well determined, then the energy of the neutrino is also determined accurately. This was done in NAL #21 by placing the detection apparatus far downstream of the end of the

decay tunnel. This minimized the largest source of uncertainty, the parallax due to the long decay tunnel.

Recently, for other reasons (muon shielding), the proposed bubble chamber position has been moved far downstream. The new geometry is quite favorable to determining θ_ν accurately and, therefore, E_ν .

In order to perform the experiment some external information may be useful or necessary.

(1) External detection of a neutrino interaction would be helpful, since the hydrogen rates are low and the number of pictures taken could be substantially reduced.

(2) Rough measurement of the energy into neutral pions would help distinguish whether events came from pion or kaon neutrinos in ambiguous cases.

(3) External detection of which interacting particles are muons again will eliminate ambiguities.

B) Beam and Rates

The rate calculations are based on the following parameters and results are shown in Figure 4 for pions and Figure 5 for kaons.

Primary Proton Beam:

400 GeV

2×10^{13} interacting/pulse

420 pulses/hour

Hadron Beam:

$\frac{\Delta p}{p} = .10$

$\Delta\Omega = 16 \text{ } \mu\text{sr}$

Yield curves of Awschalam ()

(i.e., 30 pions/GeV/sr/int. proton at 120 GeV/c)

$$\Delta\theta_{\text{horiz}} = \pm 0.38 \text{ mr}$$

$$\Delta\theta_{\text{vert}} = \pm 0.14 \text{ mr}$$

Neutrino Beam:

400 meter decay tunnel

1000 meter muon shield

3 meter diam. apparatus and

1.4 meter diam. apparatus (representing fiducial area cut for
better resolution)

A description of a possible beam design for the target box was given in NAL Proposal #21 and we will not repeat it here. The number of pions/pulse sent down the decay tunnel is shown in Figure 4. The number of pions/pulse that decay to give neutrinos is also shown. Finally, those decay neutrinos that strike the sensitive volume of the bubble chamber is shown. Similarly the results for kaons is shown in Figure 5.

Figure 6 shows the number of neutrinos interacting in the bubble chamber per hour for the chamber full of liquid hydrogen and for neon. Note that there is roughly an event every 3 pulses in neon and every 50 pulses in hydrogen. Simultaneously point A (B or C) is measured for both pion and kaon neutrinos.

C) Resolutions

The use of the neutrinos from pion decay, rather than those from k-decay, gives somewhat poorer resolution on the neutrino energy. Figure 7 shows the standard deviation on the neutrino energy ($30 < E_\nu < 80 \text{ GeV}$) as a function of energy. The standard deviation ranges $.07 < \sigma_\nu/p_\nu < .18$. At the lowest energies, this comes primarily from the finite ($\pm .05$) spread in pion energies in the hadron beam and at higher energies, the parallax of the decay region as viewed by points

Figure 31

decay shield
400m 1000m
Approx.

Total π 's in beam
 $\frac{\Delta p}{p} = 0.10$ FWHM
 $\Delta\Omega = 16 \mu\text{sr}$
 2×10^{13} interact protons

Pion Neutrinos

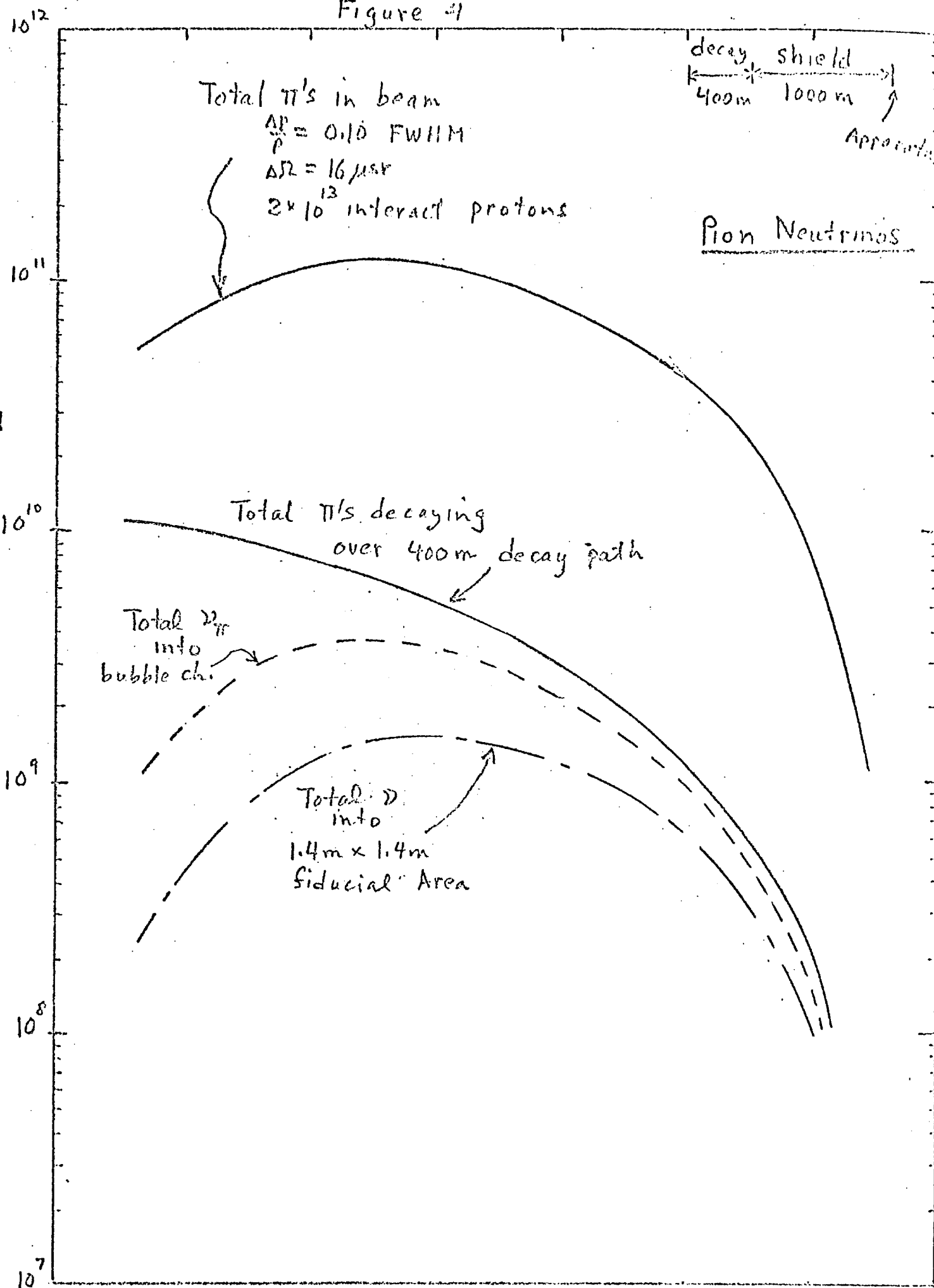
Yield

Total π 's decaying
over 400m decay path

Total ν_{π}
into
bubble ch.

Total ν
into
1.4m x 1.4m
fiducial Area

50 100 150 200 250 300
 $E_{\pi}(\text{GeV})$



Kaon Neutrinos

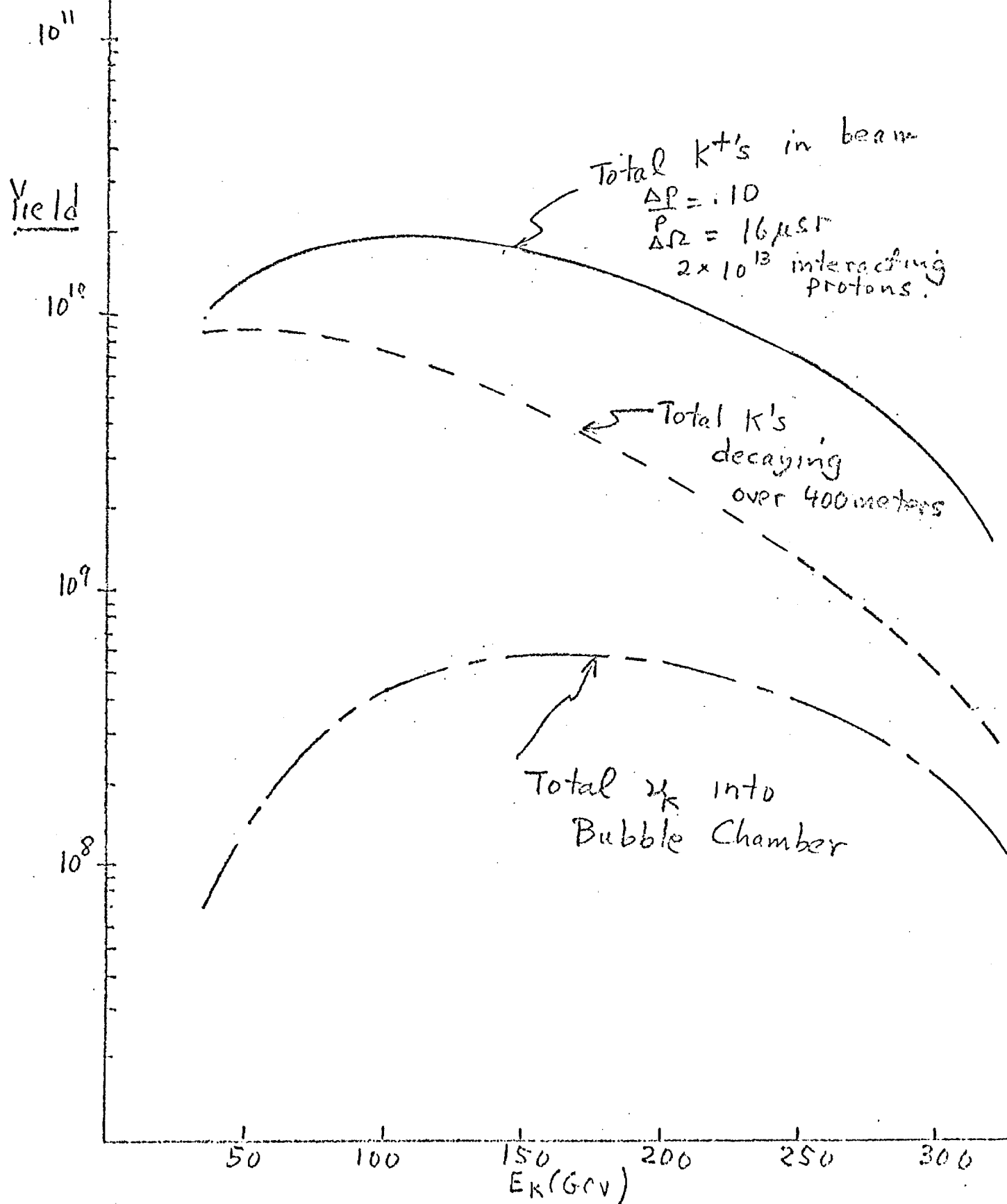


Figure 6

Data Rates in Bubble Chambers

— pion neutrino
- - - kaon neutrino

Note.
points
A or B or C or D
are measured
simultaneously
for pion
and
kaon
neutrino

Events
per
Hour

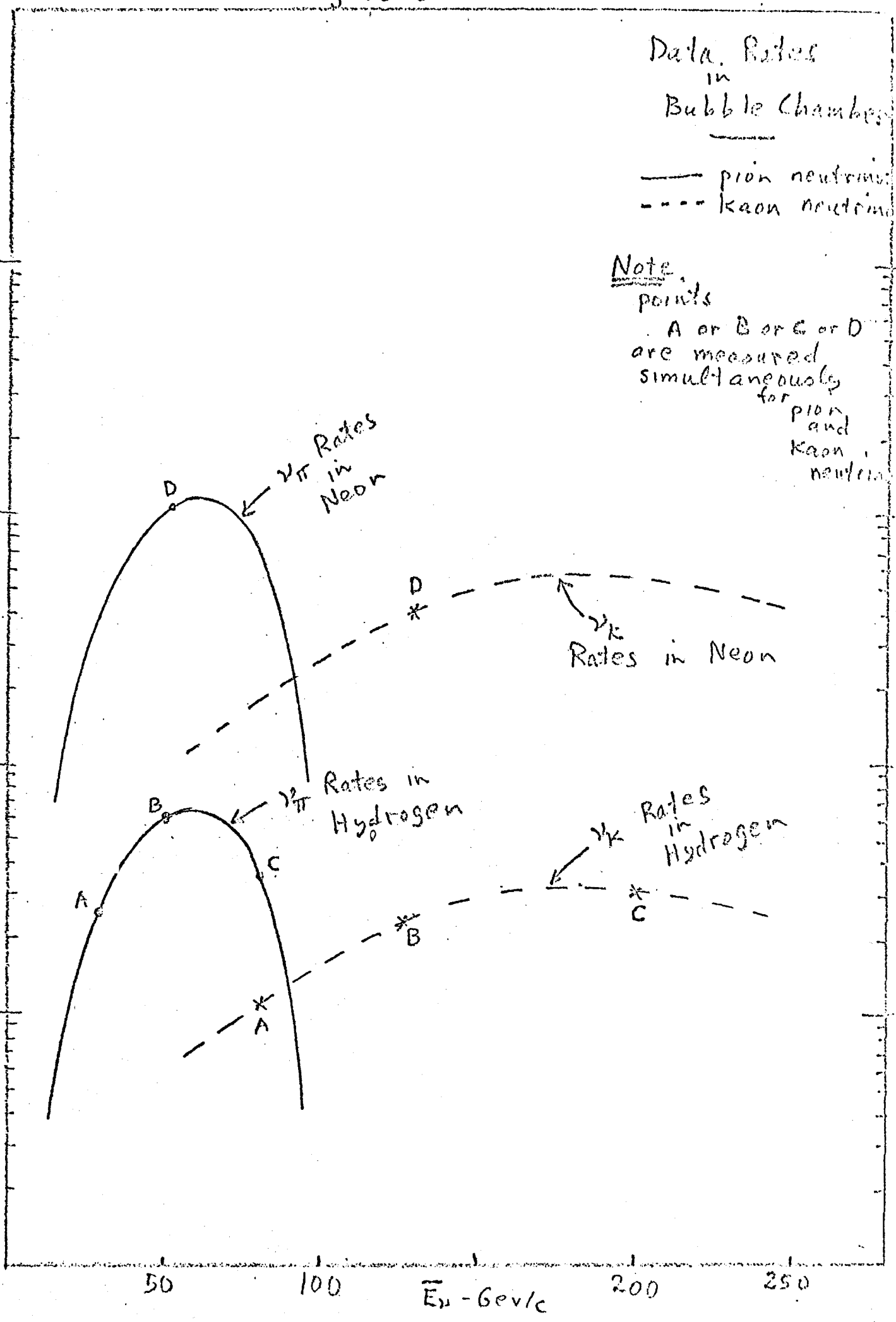
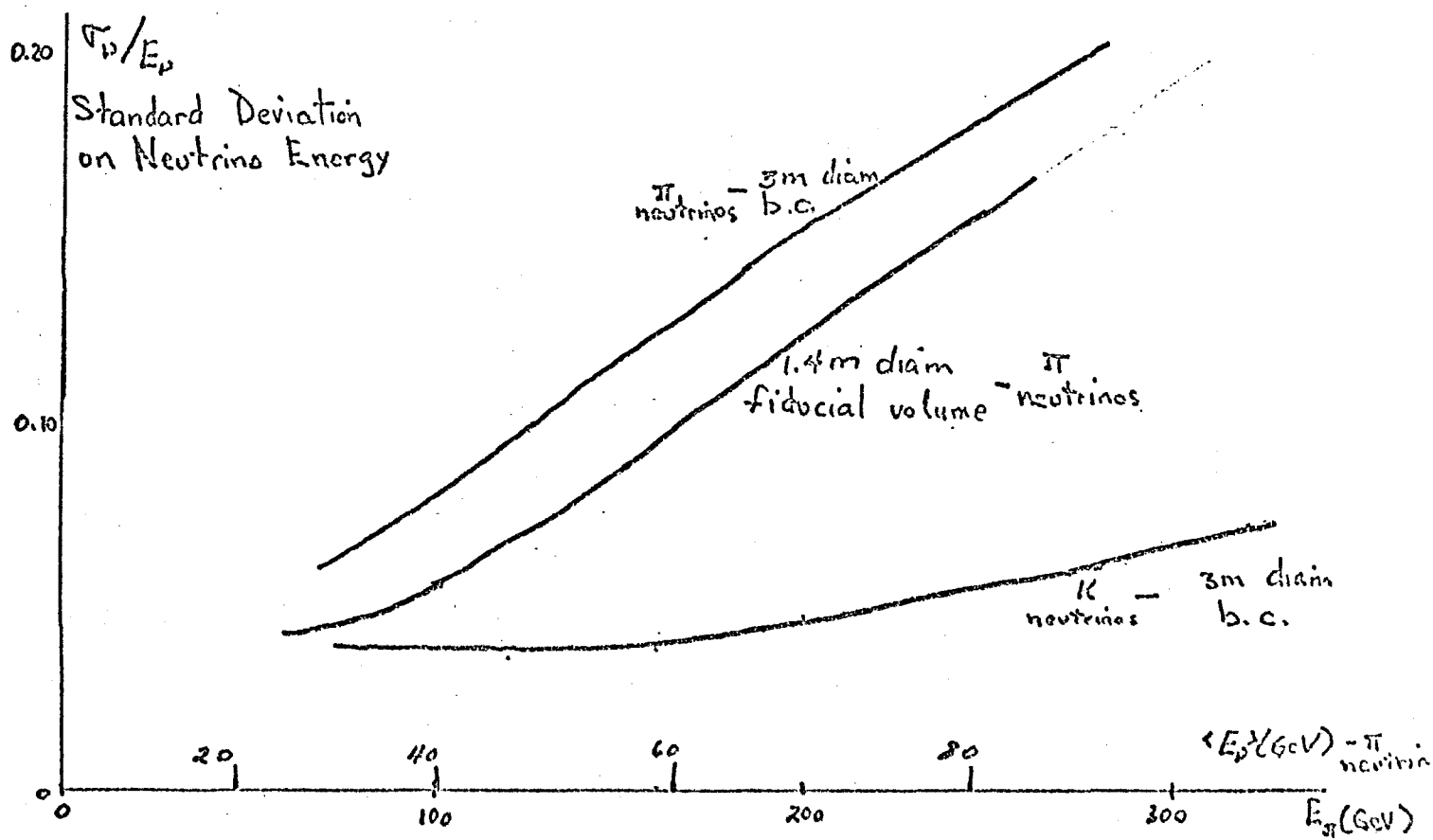
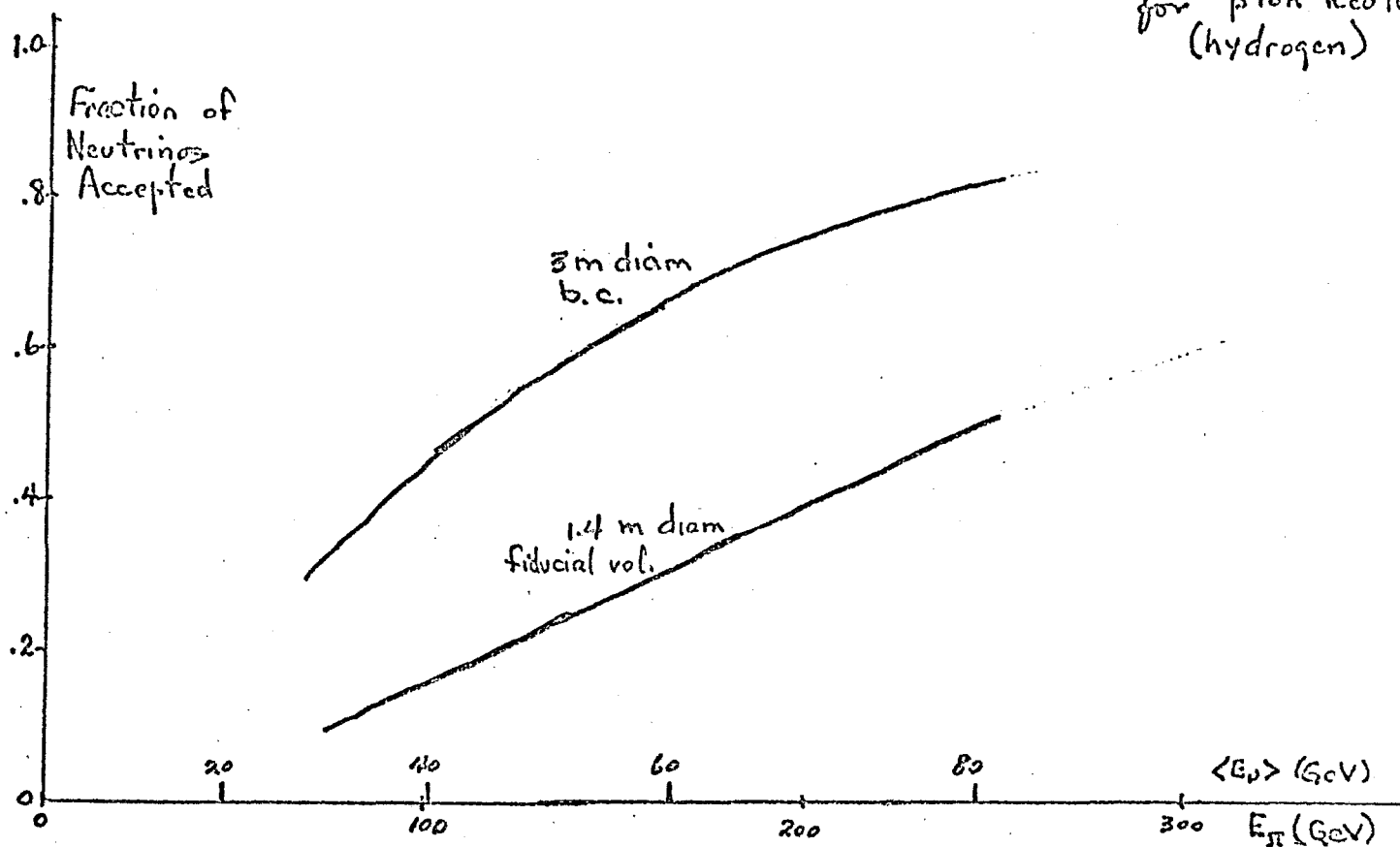


Figure 7

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Bubble chamber
resolution
for pion neutrino
(hydrogen)



near the outside edge of the bubble chamber.

This latter error may be somewhat reduced by choosing a smaller fiducial volume inside the bubble chamber. For example, a 1.4 meter diameter fiducial volume gives a standard deviation at $E_\nu = 80$ GeV of $\sigma_\nu/p_\nu \approx 0.15$. Even though this fiducial volume contains less than one quarter the volume of hydrogen, the useful rate is 0.60 of the unrestricted fiducial volume. This is due to the sharp radial distribution of neutrinos in a monoenergetic beam.

Also of consequence is the resolution on kinematic parameters for deep inelastic scattering. The most commonly used are $y = \frac{E_\nu - E_\mu}{E_\nu}$ and $x = q^2/2M(E_\nu - E_\mu)$, where $q^2 = 2 E_\nu E_\mu (1 - \cos\theta)$. These cover the range $0 < x < 1$, $0 < y < 1$. Because we use the bubble chamber to measure the outgoing muon, the resolution on its momentum and angle should be quite good. In estimating the expected resolutions on these parameters, we have assumed

- (1) $\Delta E_\mu/E_\mu = .03$ is the standard deviation on the muon energy;
- (2) the resolution on E_ν is given by Figure 7 for the entire bubble chamber fiducial volume;
- (3) the resolution on θ is set by multiple scattering considerations and the standard deviation for point measurements in the bubble chamber is 0.33 mm.
- (4) The final hadron system, whose charged component is measured to about $\pm 3\%$, is assumed to be measured in hydrogen to $\pm 20\%$ overall.* This would be substantially improved in neon.

The multiple scattering error on θ means that there is a minimum detectable q^2 and x . The errors in energy measurement create an error in Δy and a fractional

* Substantial improvement could be expected if peripheral equipment, such as that described in Proposal 9A, is employed to measure the electromagnetic component.

error in x . These errors are functions of y only. Figure 8 shows typical resolutions as a function of y for $E_\nu = 50$ GeV.

It should be noted that the kaon neutrinos produce considerably smaller errors. Figure 7 shows the error in neutrino energy as a function of energy. The resolution on the kinematic parameters (x,y) is proportionately better.

D) External Equipment Required,

The experiment requires some information obtained external to the bubble chamber itself, but no modifications to the chamber.

For the neon running possibly nothing external is required. The rate is high enough to take a picture every expansion. Pion and kaon neutrinos can be separated by measuring the visible energy in the chamber and muons from the interaction could be distinguished from pions since the chamber is about six interaction lengths for pions. An external plate would, however, better enable us to distinguish muons and thereby use the whole chamber for interactions.

For hydrogen or deuterium running certain external information is valuable or necessary.

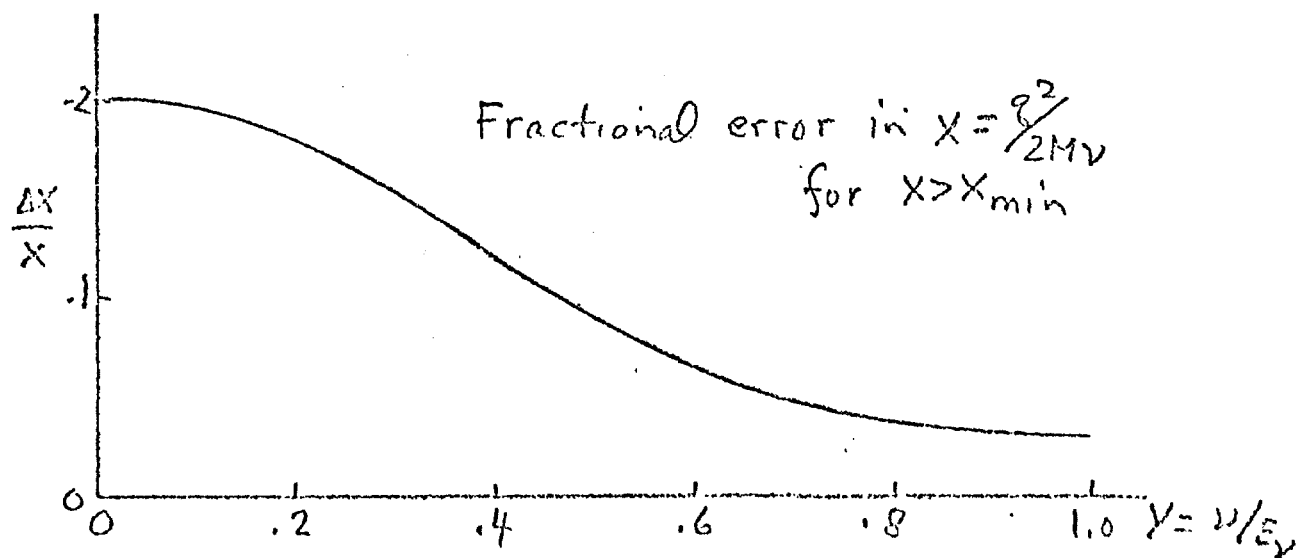
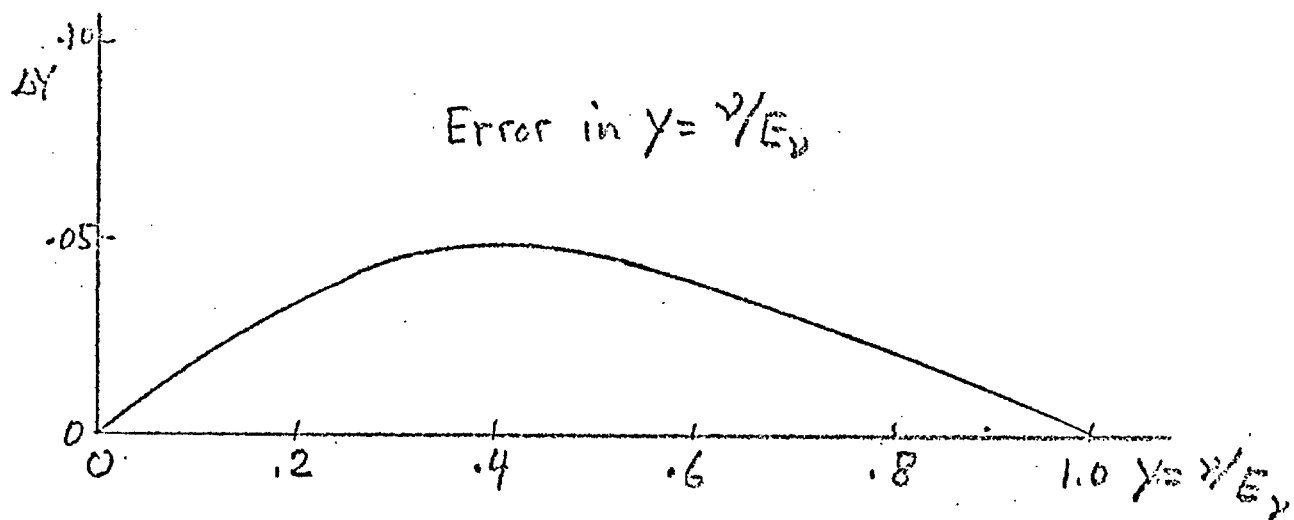
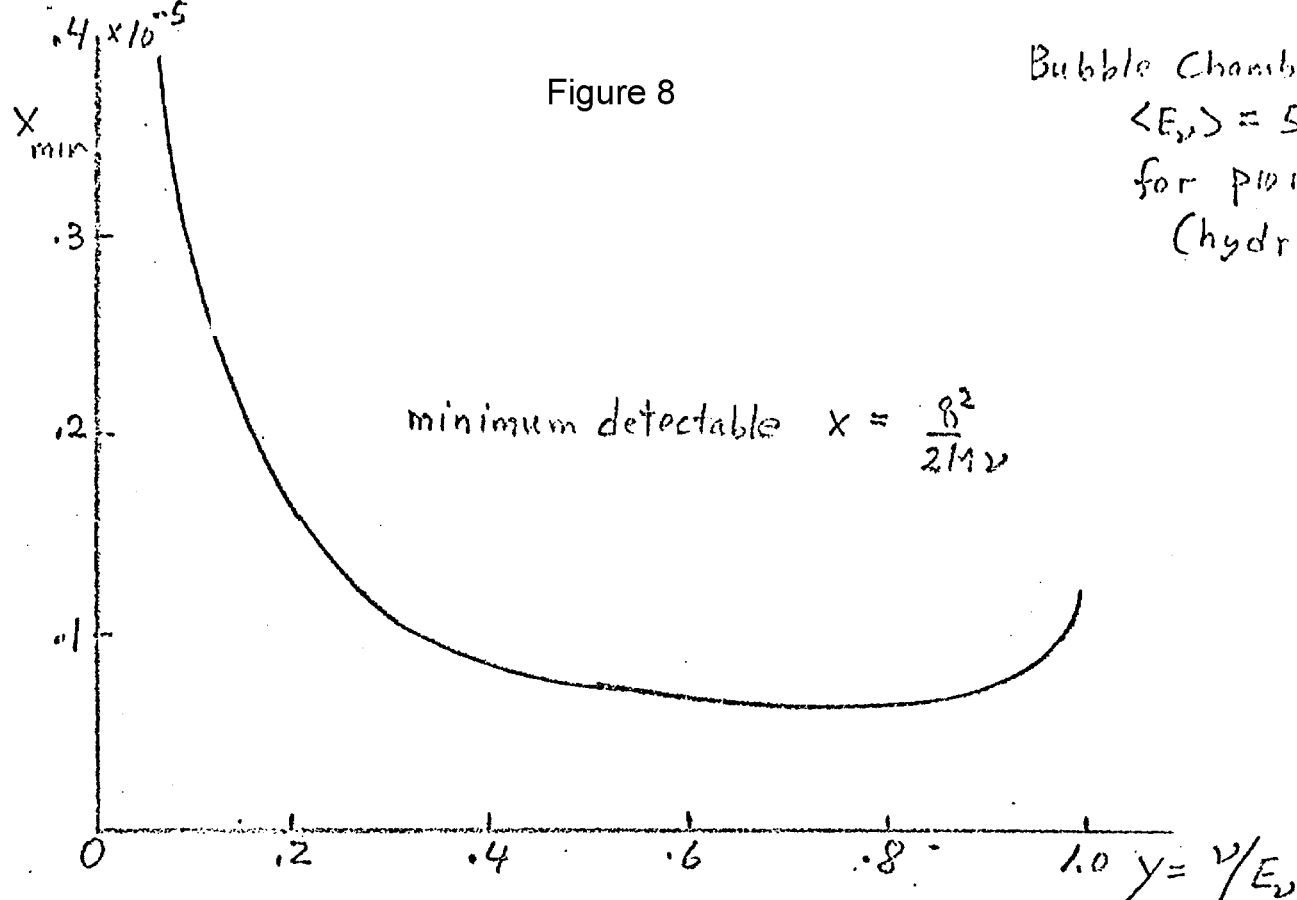
A simple system to detect that an interaction took place in the chamber will reduce the number of pictures taken for 250K expansions to less than 10K.

Distinguishing pion neutrinos from kaon neutrinos and thereby determining the neutrino energy might be ambiguous if just the visible energy in the chamber is used. A rough measure of the energy in neutral pions will eliminate this problem. This could be done externally with a coarse external Pb-Scintillator sandwich array or if a device like the π^0 Quantameter for NAL Proposal #9A is built into the chamber it could be used.

For high energy muons, a possible ambiguity with pions exists which

Figure 8

Bubble Chamber Resolution
 $\langle E_\nu \rangle = 50 \text{ GeV}$
 for π^0 neutrinos
 (hydrogen)



requires external apparatus. The tracks will have to be followed through many interaction lengths of material to pick out the muons unambiguously. This could be done using the calorimeter from one of the proposed counter-spark chamber experiments or the hadrometer proposed in NAL B.C. Proposal #9A or a plate in the chamber as proposed in NAL #53.

It should be emphasized that the requirements on the accuracy of these external measurements is not great. They are only used to distinguish ambiguities and do not directly affect the accuracy of the experiment. We would hope that no large external apparatus be built specifically for this experiment and either pieces from the counter experiments or equipment such as that proposed for NAL #9A be used.

E) Experimental Needs

- 1) Monoenergetic beam.
- 2) Equipment external to the bubble chamber.
- 3) Bubble chamber.
- 4) Analysis facilities.

A monoenergetic beam facility at NAL will broaden the potential of Area 1. It can be used for both bubble chamber and counter experiments and has other assets, such as producing a good muon beam. We would like to strongly participate both in the design and implementation of such a facility.

The usefulness of this type of beam in the bubble chamber has been presented in this proposal. We plan a broadened participation in actually carrying out this experiment. The external equipment to be used has been left somewhat open. It will be equipment such as is suggested in other bubble chamber proposals and a collaboration quite likely could be formed.

Measuring facilities will be available at Caltech to analyze the film. A POLLY film digitizer, which will be operational during 1971, is presently being constructed.

F) Conclusions

We propose here an exposure using the NAL 30m³ bubble chamber. The unique feature of the experiment is the use of a momentum defined neutrino beam. This helps simplify the "hybrid" nature of studying high energy neutrino collisions, and makes the experiment easily and reliably interpretable. Some simple external apparatus is still needed to eliminate certain ambiguities.

A summary of the number of events expected in an experiment of the size proposed is given in the table below.

Incident Particle	Momentum (GeV)		Liquid in B.C.	Expansions	Events **	
	ν_π	ν_k			ν_π	ν_k
ν	30	80	Hydrogen	70K	500	165
	50	125		40K	620	310
	80	200		70K	580	550
$\bar{\nu}^*$	50			70K	600	-
ν	50	125	Deuterium	90K	2800	1400
$\bar{\nu}^*$	50			160K	2500	-
ν	50	125	Neon	250K	71,000	35,000

* Assumes $\sigma_\nu = \sigma_{\bar{\nu}}$

** Assumes $\sigma = .6 \cdot 10^{-38} \times E_\nu$

References.

1. Bjorken and Paschos, SLAC Pub. 678 (1969).
2. Budagov, et al, Phys. Letters 30B, 364 (1969).
3. L.M. Lederman, Proceedings of the International School of Physics "Enrico Fermi" XXXII (Academic Press, 1964), p. 186.
4. D.O. Caldwell, et al, Phys. Rev. Letters 23, 1256 (1969).
5. S. Adler, Phys. Rev. 135, B963 (1964).
6. J. Lovseth and J. Froyland, Il Nuovo Cimento 53, 1 (1968).
7. K. Borer, et al, Phys. Letters 30B, 572 (1969) and M. Holder, Lettere al Nuovo Cimento 3, 445 (1970).
8. D.J. Gross and C.H. Llewellyn Smith, Nuclear Physics B17, 277 (1970) and C.H. Llewellyn Smith, Nuclear Physics B17, 277 (1970) and Reference 1.
9. S.D. Drell, et al, Phys. Rev. Letters 22, 744 (1969) and SLAC pub.'s 606, 645, and 685.
10. See review by C.H. Llewellyn Smith, Th. 1188-CERN (1970).
11. H. Harari, Phys. Rev. Letters 22, 1078 (1969) and Phys. Rev. Letters 24, 286 (1970).
12. C. Jarlskog, Nuclear Physics 75, 659 (1966).
13. D. Fryberger, Phys. Rev. 166, 1379 (1968).
14. C. Jarlskog, University of Lund preprint (April 1970).

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Revised: July 14, 1971

ABSTRACT

We propose to use the NAL 30m³ bubble chamber to study $\nu(\bar{\nu})$ interactions. The scheme used in NAL Experiment #21 to obtain incident neutrinos with known momentum and angle is employed. We will cover the energy region 30-80 GeV using pion neutrinos and simultaneously the region 80-200 GeV with kaon neutrinos.

The experiment is capable of the following physics:

I) Studying in an unambiguous and systematic free way the behavior of σ_{total} and $\frac{d^2\sigma}{dq^2 d\nu}$ vs. E_ν from 30-200 GeV by using hydrogen in the Bubble Chamber.

II) Making meaningful and clean comparisons of $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ cross-sections and their corresponding differential cross-section by comparing hydrogen and deuterium and reversing the polarity of the hadron beam.

III) Studying the details of the final hadronic state in hydrogen, deuterium, and neon.

IV) If the W-Boson exists and can be produced, information on its decay modes will be obtained.

We request 250K expansions, each, for the chamber filled with hydrogen, deuterium, and neon. This will enable us to obtain ~5% measurements on the various total cross-sections and about 100K inelastic events in neon.

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I. PHYSICS JUSTIFICATION

A. Introduction

We propose to use the monoenergetic neutrino beam incident on the NAL fifteen-foot bubble chamber to carry out an investigation on the details of neutrino interactions in the energy range $30 < E_\nu < 200$ GeV.

The bubble chamber pictures, together with information on the monoenergetic beam, suffice to allow a determination of which outgoing track is the muon in a large fraction of the events. We believe, therefore, that much of the research outlined in this proposal can be carried out without additional muon detection equipment.

The techniques described in NAL proposal #21, and presently being carried out in the Neutrino Laboratory, could be used to define the incident momentum and angle of the neutrinos. In this proposal, however, we emphasize the use of both pion and kaon neutrinos. The pion neutrinos give larger event rates, but the energy of the incident neutrino is lower and the resolution poorer.

Many of the advantages of the narrow band (monoenergetic) neutrino beam are well known: well-defined incident energy, simple and direct monitoring for absolute normalization, etc. We should like to stress that the use of known energy neutrinos substantially reduces the reliance on other muon identification. If the hadrons created by the neutrino interaction have transverse momenta of the same order as that observed in hadron collisions, for example, then it is possible to distinguish the muon from the

hadrons in each event over essentially all of the kinematic range. Even if the average transverse momentum of hadrons were to grow with q^2 or v , it would still be possible to distinguish the muon so long as the average transverse momentum were a small fraction of the maximum value that is allowed kinematically (e.g. this condition is automatically satisfied for high multiplicity). We expect to determine the gross character of the transverse momentum distribution while running experiment #21, and therefore to delineate precisely our needs for an external muon identifier. At best, we require no detector; at worst, the detector required is of modest size, definitely no larger than that described in Section IID.

Our motivation in making this proposal is twofold:

(a) to aid in the interpretation of our data on deep inelastic scattering off iron which will have been done in Experiment #21;
 (b) to answer questions which we do not expect to be answered in the counter experiment. These goals (for different chamber fillings) include:

I) Hydrogen exposure: σ_T and $\frac{d\sigma}{dq^2 dv}$ vs. E_ν can be measured on protons in a way free of systematic errors. For each event, details of the interaction including the behavior of the hadronic system can be studied. Since event rates are low for counter or bubble chamber experiments in hydrogen, it seems reasonable to obtain as much information as possible about each event.

II) Deuterium exposure: By using neutrinos and antineutrinos, a clean comparison of $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ and their corresponding inelastic differential cross sections can be obtained.

By using both the hydrogen and deuterium exposure we can establish over what kinematic region in q^2 and ν the differential cross-section for inelastic neutrino scattering off complex nuclei is simply the sum of the incoherent scattering off the constituent neutrons and protons.

III) Neon exposure: A large number of inelastic events will be obtained with the advantages of a bubble chamber. For example, there is a uniform solid angle acceptance, and the ability to see the vertex and study details of the interaction. If the W exists and can be produced, details of the decay modes will be learned. Certain rare or forbidden event types, discussed below, can also be looked for.

It should be noted that with the exception of $\frac{d\sigma}{dq^2 d\nu}$ and the study of the ν and q^2 behavior of the hadronic system with hydrogen and deuterium, none of the above require a muon detector. Further, some fraction of the hydrogen events will be obvious from their charge configuration as to the muon identification ($\nu + p \rightarrow \mu^- + \text{hadrons}$ requires a multiplicity of four or greater in the hadron system to be ambiguous.)

We describe in somewhat more detail below the physics of these measurements.

B. σ_T vs. E_ν on Hydrogen

Following Bjorken and Paschos⁽¹⁾ the cross-sections for $\nu + p \rightarrow \mu^- + \text{hadrons}$ can be written in terms of form factors W_1 , W_2 , and W_3

$$\frac{d^2\sigma}{dq^2 dv} = \frac{E-v}{E} \frac{G^2}{2\pi} \cos^2 \frac{\theta}{2} \left[W_2(q^2, v) + 2 \tan^2 \frac{\theta}{2} \left(W_1(q^2, v) + \frac{2E-v}{2M} W_3(q^2, v) \right) \right] \quad (1)$$

A number of authors have shown that integrating over the differential cross-section and assuming that W_1, vW_2 and vW_3 are scale invariant (i.e., functions only of $\frac{v}{q^2}$) leads to a linearly rising cross-section.

Experiments at CERN⁽²⁾ using a heavy liquid bubble chamber measured the total cross-section up to 12 GeV, which are shown in Fig. 1. A linear fit to the events with $E_\nu > 2$ GeV gives

$$\sigma_T = (0.51 \pm 0.13) \frac{G^2}{\pi} \text{ ME/nucleon}$$

where the errors are statistical only. As one goes to NAL energies it is important to determine whether σ_T continues to rise linearly.

A turnover in the rising cross-section could be caused by a W-Boson. For example, if the W exists it has a propagator term and $G \rightarrow \frac{G}{1 + q^2/M_W^2}$ in Formula (1). This term damps $\frac{d\sigma}{dq^2}$ at high q^2 and therefore will affect the total cross-section. Figure 2 shows the effect of this propagator on the total cross-section as a function of S/M_W^2 where $S = 2 M_p E_\nu$.

A turnover might also result from a breakdown of scale invariance which would reflect on the basic hadronic structure.

A measurement of the total cross-section is not easy:

In wide band beams, the following problems arise. Preliminary to any neutrino measurements, the hadron flux must be measured accurately at all energies and production angles from the same target that is used for the neutrino beam. At CERN,

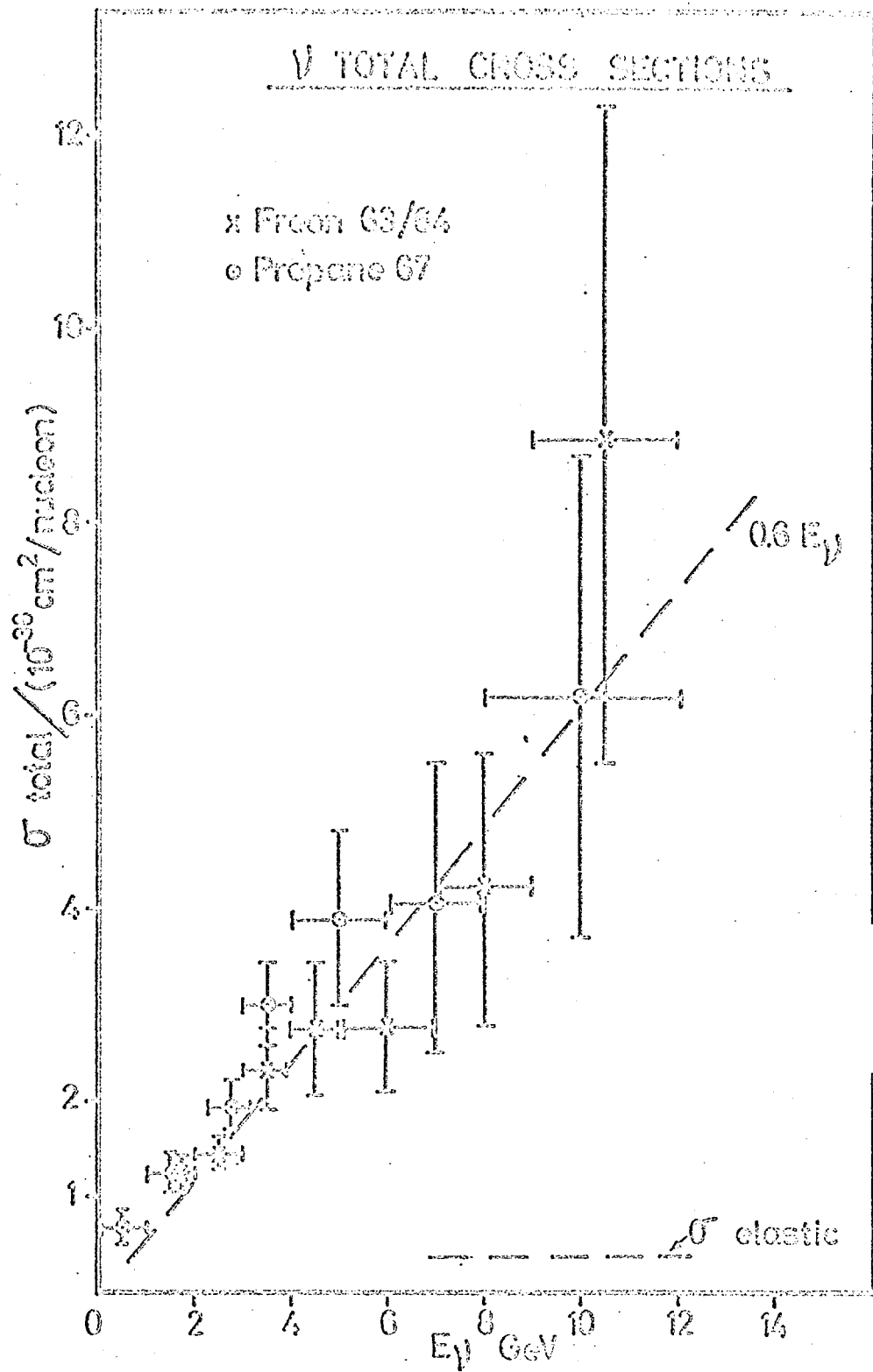
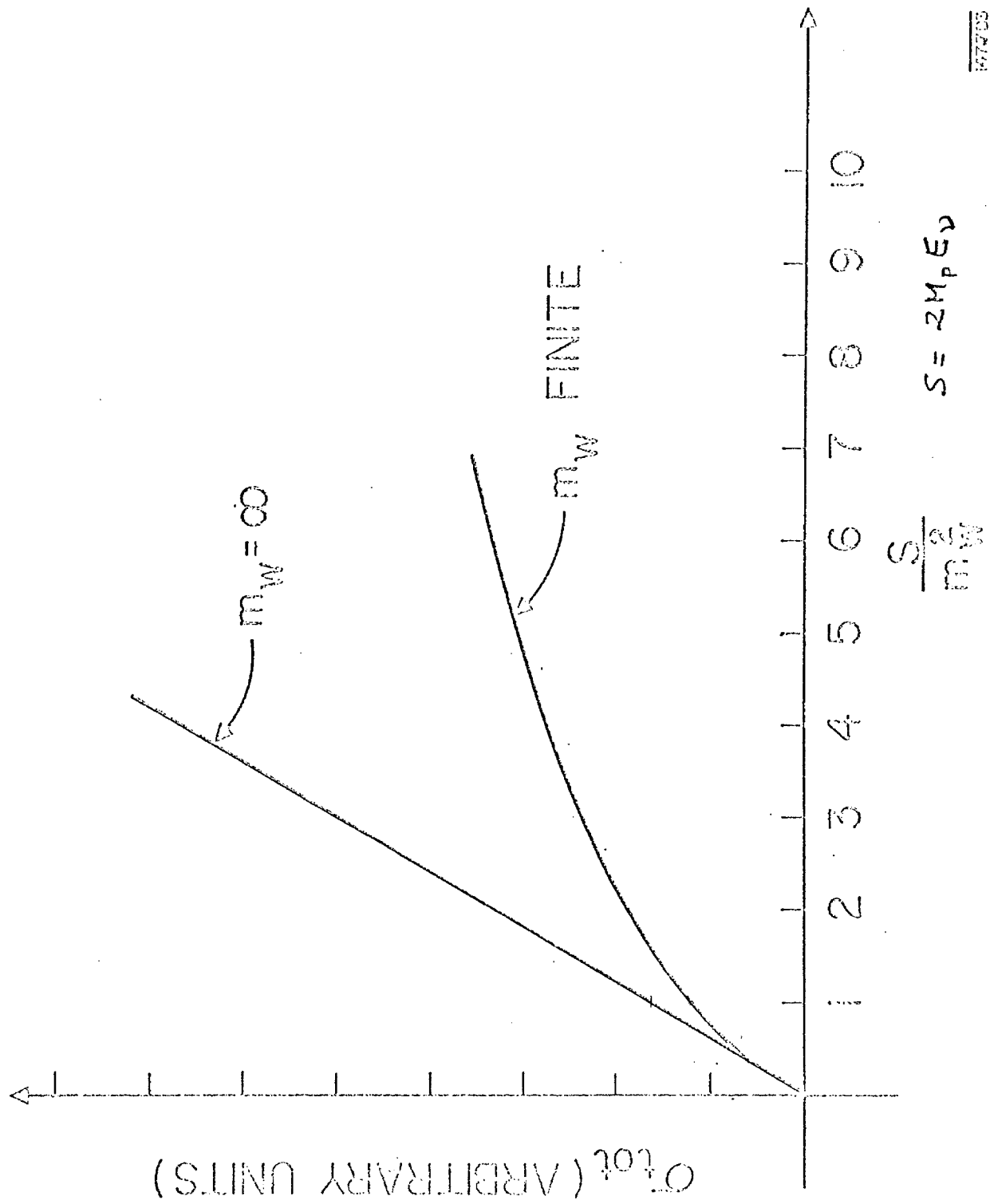


Figure 1

this measurement was ultimately done by putting the target in the bubble chamber⁽³⁾. The hadron flux is then folded into the acceptance of the focussing system to be used and one obtains the predicted neutrino flux. The resulting neutrino flux curves are expected to fall rapidly with energy. A small systematic error in energy for observed neutrino events creates a rather large flux, and hence cross-section, error. The narrow band beam nicely eliminates these problems. Also monitoring the beam becomes both simpler and more direct.

A second serious difficulty which exists is the use of $A \gg 1$ targets. The A -dependence of the cross-section for neutrino scattering is completely unknown. Experiments show that the total photon cross-section on nuclei is proportional to $\sim A^9$ at 20 GeV⁽⁴⁾. Adler⁽⁵⁾, using PCAC, has predicted a differential cross-section at zero degrees that should be proportional to $A^{2/3}$. However, Lovseth and Froyland⁽⁶⁾ get a cross-section proportional to A at all but the smallest angles. Attempts have been made at CERN⁽⁷⁾ to measure the A -dependence at low energies but the results are rather inconclusive. In view of all this it seems very important to do the total cross-section on hydrogen to obtain unambiguous results.

We propose to obtain this energy dependence on hydrogen and with a momentum defined beam. We will be able to obtain $\sim 5\%$ measurements at 30, 50 and 80 GeV with $\sim 50K$, $25K$, and $50K$ expansions respectively, and simultaneously with kaon neutrinos $\sim 10\%$ measurements at ~ 80 , 125 and 200 GeV.



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Fig. 2

C. Comparison of $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ Using Hydrogen and Deuterium

Reversing the polarity of the hadron beam, negative pions are selected and thereby make a beam of antineutrinos. It should be noted that the unique sign selection in our hadron beam makes the ν contamination in the $\bar{\nu}$ beam negligible and vice versa. Filling the chamber with deuterium and hydrogen and reversing the polarity of the beam enables us to measure $\sigma_{\nu p} : \sigma_{\nu n} : \sigma_{\bar{\nu} p} : \sigma_{\bar{\nu} n}$ at the same incident energy with little systematic error.

A variety of predictions for these ratios and certain sum rules have been obtained from different models of highly inelastic neutrino scattering. For example, parton models⁽⁸⁾ predict

$$\sigma_{\nu} > \sigma_{\bar{\nu}}$$

and

$$\sigma_{\nu p} + \sigma_{\nu n} + \sigma_{\bar{\nu} p} + \sigma_{\bar{\nu} n} \leq 1.72 \frac{G_{ME}^2}{\pi}.$$

Drell's field theory parton model⁽⁹⁾ for the region $\omega = \frac{2M_p \nu}{q^2} \gg 1$ predicts $\frac{(d\sigma_{\bar{\nu}}/d\omega)}{(d\sigma_{\nu}/d\omega)} = \frac{1}{3}$ for $\omega \gg 1$.

In contrast diffraction models⁽¹⁰⁾ predict $\sigma_{\nu p} = \sigma_{\nu n} = \sigma_{\bar{\nu} p} = \sigma_{\bar{\nu} n}$ in the region where the models are valid. If the leading trajectories continue to dominate for $\omega \gg 1$, νW_3 is scale invariant. This leads to the result

$$\frac{(d\sigma_{\bar{\nu}}/d\omega)}{(d\sigma_{\nu}/d\omega)} = 1$$

for $\omega \gg 1$.

Harari's⁽¹¹⁾ model, where only the Pomeron contributions are scale invariant and $\nu W_3 \rightarrow 0$ for q^2 large, predicts

$\sigma_{\nu} = \sigma_{\bar{\nu}}$ over most of the physical region.

Independent of the validity of any of these models, it is apparent that information on the relations between these cross-sections is very important in determining the nature of the basic hadronic structure. Unraveling these cross-sections in the counter-spark chamber experiments is very difficult since it is hard to distinguish a A-dependent effect from a difference in scattering off neutrons and protons. Using hydrogen and deuterium as targets is ideal for making unambiguous measurements.

D. Deep Inelastic Scattering

Information on the distribution of events as a function of q^2 and ν will result from the hydrogen measurements. Although this sample will only consist of ~ 1 -2K events it will be valuable since it is free of all A-dependent effects and will have very good resolution in q^2 and ν . Details about the final hadron state can be studied; for example, the multiplicity as a function of q^2 and ν and momentum and angular distributions of the pions, etc. A direct check of the local $SU(3) \times SU(3)$ current algebra will be possible through Adler's relation

$$\lim_{E_{\nu} \rightarrow \infty} \frac{d\sigma^{\bar{\nu}p}}{d|q^2|} - \frac{d\sigma^{\nu p}}{d|q^2|} = \frac{G^2}{\pi} (\cos^2\theta_c + 2 \sin^2\theta_c),$$

where θ_c is the Cabibbo angle.

A comparison of the events from the hydrogen and deuterium exposures is important for the interpretation of the inelastic neutrino form factors obtained in complex nuclei. The kinematic region in q^2 and ν over which the inelastic neutrino scattering

off complex nuclei is simply the sum of the incoherent scattering off the constituent neutrons and protons must be established experimentally.

A second test of the local $SU(3) \times SU(3)$ current Algebra will follow from Adler's relation

$$\lim_{E_\nu \rightarrow \infty} \frac{d\sigma^{\bar{\nu}n}}{d|q^2|} - \frac{d\sigma^{\nu n}}{d|q^2|} = \frac{-G^2}{\pi} (\cos^2\theta_c - \sin^2\theta_c).$$

A test of the local $U(6) \times U(6)$ current Algebra (in the absence of spin zero gluons) has been found by Fritzsch and Gell-Mann and is given by the relation

$$\int \frac{9}{2} (F_2^{\gamma p} + F_2^{\gamma n}) - \frac{3}{4} (F_2^{\nu p} + F_2^{\nu n}) dx = 1,$$

where $F_2 = \nu W_2$ and $x = \frac{q^2}{2M\nu}$. If the inelastic scattering is incoherent those relations will, of course, be checked off complex nuclei. Otherwise, the less accurate data off deuterium can be used.

The exposure in neon will present a sample of events with all the advantages of the bubble chamber and good statistics ($\sim 100K$ events). Acceptance over q^2, ν will be uniform, resolution good, and details about each event available. Questions about whether the cross-section goes to zero or remains finite at $\omega \gg 1$ can be investigated (within the limitations of A-dependent effects).

E. W-Decay Modes

If the W-Boson exists and can be produced at $E_\nu \sim 80$ GeV, details of the decay modes could be determined in neon.

(A 5 GeV W-Boson would give $\sim 10K$ events into all decay modes.)

Detection of $W \rightarrow e\nu$ would be very clean in the bubble chamber and information on the hadronic decays could be determined. The very fundamental question of the coupling of the weak interaction currents to hadronic systems can be investigated by measuring the branching ratios of the decaying boson to hadrons.

F. Conservation of Leptons

Using the two neutrino hypothesis we define muon and electron lepton numbers

$$N_{\mu} = N_{\mu^{-}} + N_{\nu_{\mu}} - N_{\mu^{+}} - N_{\bar{\nu}_{\mu}},$$

$$N_e = N_{e^{-}} + N_{\nu_e} - N_{e^{+}} - N_{\bar{\nu}_e}.$$

The conservation law conventionally assumed is that N and N_e are separately conserved. However, all experimental evidence is also consistent with the weaker hypothesis that only the sum $N_{\mu} + N_e$ and the sign of $(-1)^{N_e}$ (or $(-1)^{N_{\mu}}$) are conserved. This would allow certain reaction forbidden by the usual scheme:

$$\nu_{\mu} + \text{hadrons} \rightarrow \mu^{+} + e^{-} + \nu_e + \text{hadrons}'$$

$$\bar{\nu}_{\mu} + \text{hadrons} \rightarrow \mu^{-} + e^{+} + \bar{\nu}_e + \text{hadrons}'.$$

If this weaker form of lepton conservation is correct, several events of this type would be expected in the neon exposure.

Conservation of muon lepton number can be tested by measuring

$$\frac{\nu_{\mu} + N \rightarrow \mu^{-} + \text{hadrons}}{\nu_{\mu} + N \rightarrow \mu^{+} + \text{hadrons}}.$$

This ratio can be determined with great accuracy in this

experiment, where the energy is high and π -decay backgrounds in the reaction are small and where $\bar{\nu}$ beam contamination is very small.

The two neutrino hypothesis itself can be sensitively tested at very different energies from the original experiments. If there were only one kind of neutrino $\nu_e = \nu_\mu$ then the reactions

$$\nu + N \rightarrow \mu^- + \text{hadrons}$$

$$\nu + N \rightarrow e^- + \text{hadrons}$$

would be equal. Since $\nu_\mu \neq \nu_e$ and the neutrinos are mainly from π -decays, the first reaction predominates. A small limit on this ratio can be made in the neon exposure.

G. Neutral Currents

In the conventional first order perturbation theory of the weak interactions, the absence of neutral currents forbids reactions like:

$$\nu_\mu + p \rightarrow \nu_\mu + p$$

$$\nu_\mu + p \rightarrow \nu_\mu + \pi^+ + n$$

Since we expect approximately 200 events of the corresponding allowed reactions

$$\nu_\mu + n \rightarrow \mu^- + p \quad (\text{in deuterium})$$

$$\nu_\mu + p \rightarrow \mu^- + \pi^+ + p \quad (\text{in hydrogen and deuterium}),$$

moderately sensitive measurements of the corresponding cross section ratios are possible. The neon exposure would, of course, improve these measurements by an order of magnitude.

In addition, events of the type

$$\nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-}$$

may be looked for in neon and compared in cross-section with the 300 expected events of the type

$$\nu_{\mu} + e^{-} \rightarrow \mu^{-} + \nu_e.$$

H. Neutrino-Lepton Scattering

The single example thus far observed of a purely leptonic interaction is $\mu \rightarrow e + \nu + \bar{\nu}$. Such interactions are the cleanest means of investigating the current-current hypothesis and the detailed form of the lepton current.

A very general form for the hamiltonian⁽¹²⁾ for this process is

$$H = \sum_i (\bar{e} (C_i + C_i' \gamma_5) \Gamma_i \mu) (\bar{\nu}_{\mu} \Gamma_i \nu_e) + h.c. \quad (1)$$

where the sum extends over the various types of couplings (S,V,T,A,P). Present experimental evidence⁽¹³⁾ is such that admixtures of scalar (pseudo-scalar) and tensor amounting to 30% of the vector-axial vector part are possible. Moreover, it has been shown⁽¹²⁾ that, even if all the decay parameters from μ decay were measured to arbitrary precision and found to agree with the predictions of V-A, in fact the hamiltonian would only be restricted to the form $V-\lambda A$, where λ could be measured in μ -decay only by observing decay neutrinos. It is possible⁽¹⁴⁾ to remove this uncertainty by measuring the angular distribution for the reaction

$$\nu_{\mu} + e^{-} \rightarrow \mu^{-} + \nu_e \quad (2)$$

We estimate that we will obtain approximately 300 events of the purely leptonic process (2) in our neon exposure.

Figure 3 shows the angular distribution expected for various assumptions concerning λ .

This process presents a formidable problem of background separation, since the background from inelastic scattering from the nucleus is expected to be about 300 times as large. The handles which we can bring to bear are:

1. The observation of only a μ^- coming from the vertex. If we assume that only inelastic events with $\nu \lesssim 300$ MeV will produce no observable charged prongs, this will reduce the background ($E_\nu = 50$ GeV) by a factor of 150.
2. The lack of conservation of visible energy for the process (2) over most of the range of muon energies.
3. Two-body kinematics: θ_μ and P_μ on the outgoing μ predict the incident neutrino energy which we have independently measured.

II. EXPERIMENTAL METHOD

A. Introduction

One method for obtaining a monoenergetic neutrino beam was discussed in NAL Proposal No. 21. We briefly review the method.

In the target box a simple beam transport system which selects hadrons with $\sim \pm 5\%$ momentum bite, forms a parallel beam and sends it down the decay tunnel. Because of the narrow momentum acceptance this hadron beam is both smaller in transverse dimensions and angular divergence than a wide band system.

Figure 3

$$H = \frac{G}{\sqrt{2}} \bar{e}(1-\gamma_5)\gamma_\lambda \mu \bar{\nu}_\mu \gamma_\lambda (1-\lambda\gamma_5)\nu_e$$

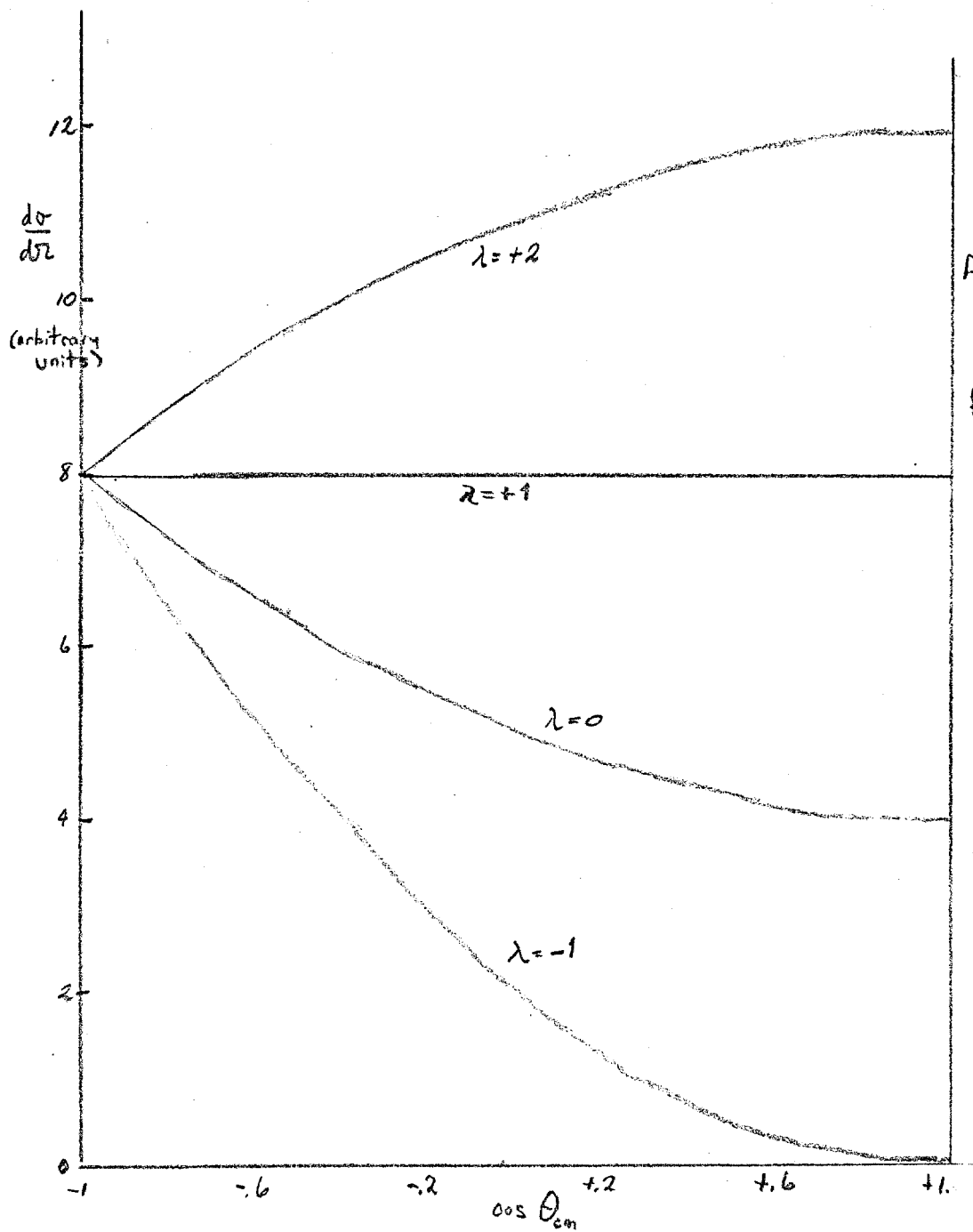
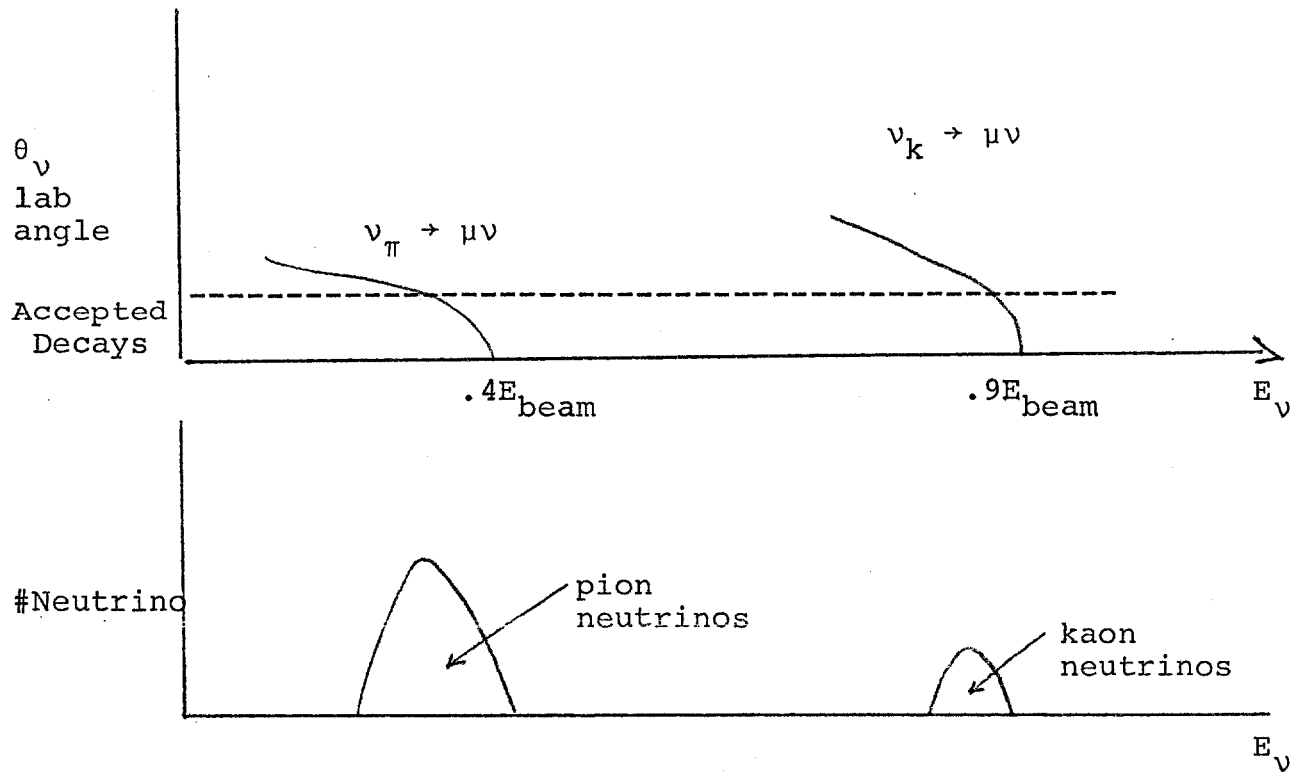


FIGURE 3
Angular Distribution
for
 $\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$
for various values
of $\lambda \equiv g_A/g_V$

V-A theory
for $\lambda = +1$.

The pions and kaons that decay in the beam tunnel yield neutrinos whose energy is correlated with their laboratory angle.



If the experimental apparatus can be placed so that θ_ν is well determined, then the energy of the neutrino is also determined accurately. This was done in NAL No. 21 by placing the detection apparatus far downstream of the end of the decay tunnel. This minimized the largest source of uncertainty, the parallax due to the long decay tunnel.

Because the bubble chamber position is 1000 m from the end of the decay tunnel, the geometry is quite favorable for determining the decay angle, θ_ν , and thus, E_ν , accurately, to within the twofold π -K neutrino ambiguity. The ambiguity is easily removed by a measurement of the visible energy in the chamber.

Total cross-sections on p and n with ν and $\bar{\nu}$ can be measured with no external information. In order to study inelastic scattering and the details of the hadronic system from hydrogen and deuterium, however, muon identification is essential. For some fraction of the events, this identification will be obvious from the charges of the outgoing tracks. It may, indeed, be possible to identify the muon from the internal kinematics of an event itself. The method is based on the assumption that hadronic transverse momenta are only a small fraction of their maximum allowable value. This assumption will be tested by Experiment No. 21. Under any circumstances, in the neutrino energy range under consideration, the muon production angle is very small over most of the kinematics plane, so that a small area external muon identifier will have an acceptable detection efficiency.

B. Beam and Rates

The rate calculations are based on the following parameters and results are shown in Figure 4 for pions and Figure 5 for kaons.

Primary Proton Beam:

400 GeV

2×10^{13} interacting/pulse

420 pulses/hour

Hadron Beam:

$\Delta p/p = .10$

$\Delta\Omega = 16 \text{ } \mu\text{sr}$

Yield curves of Awschalom

(i.e., 30 pions/GeV/sr/int. proton at 120 GeV/c)

Figure 4

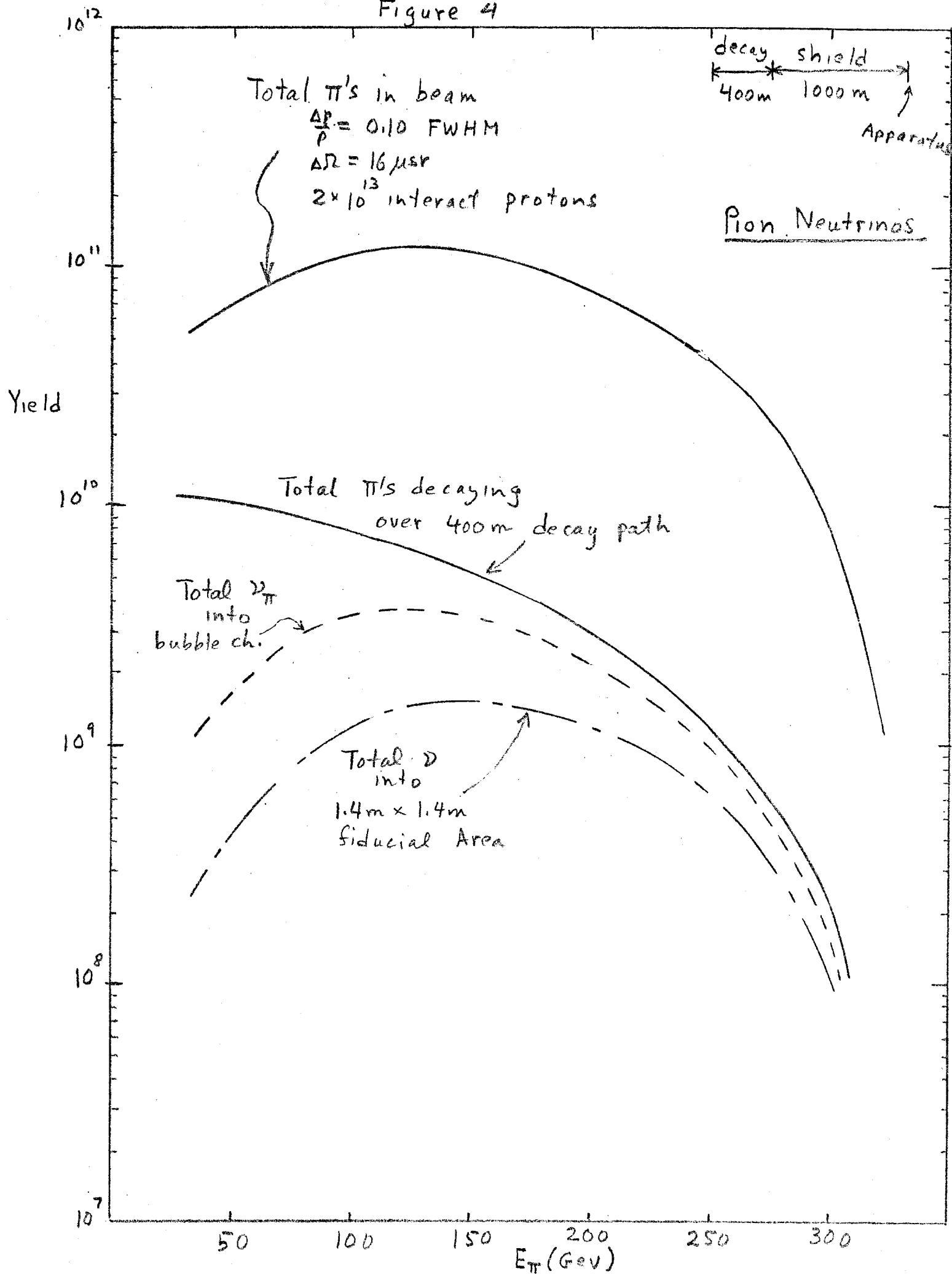
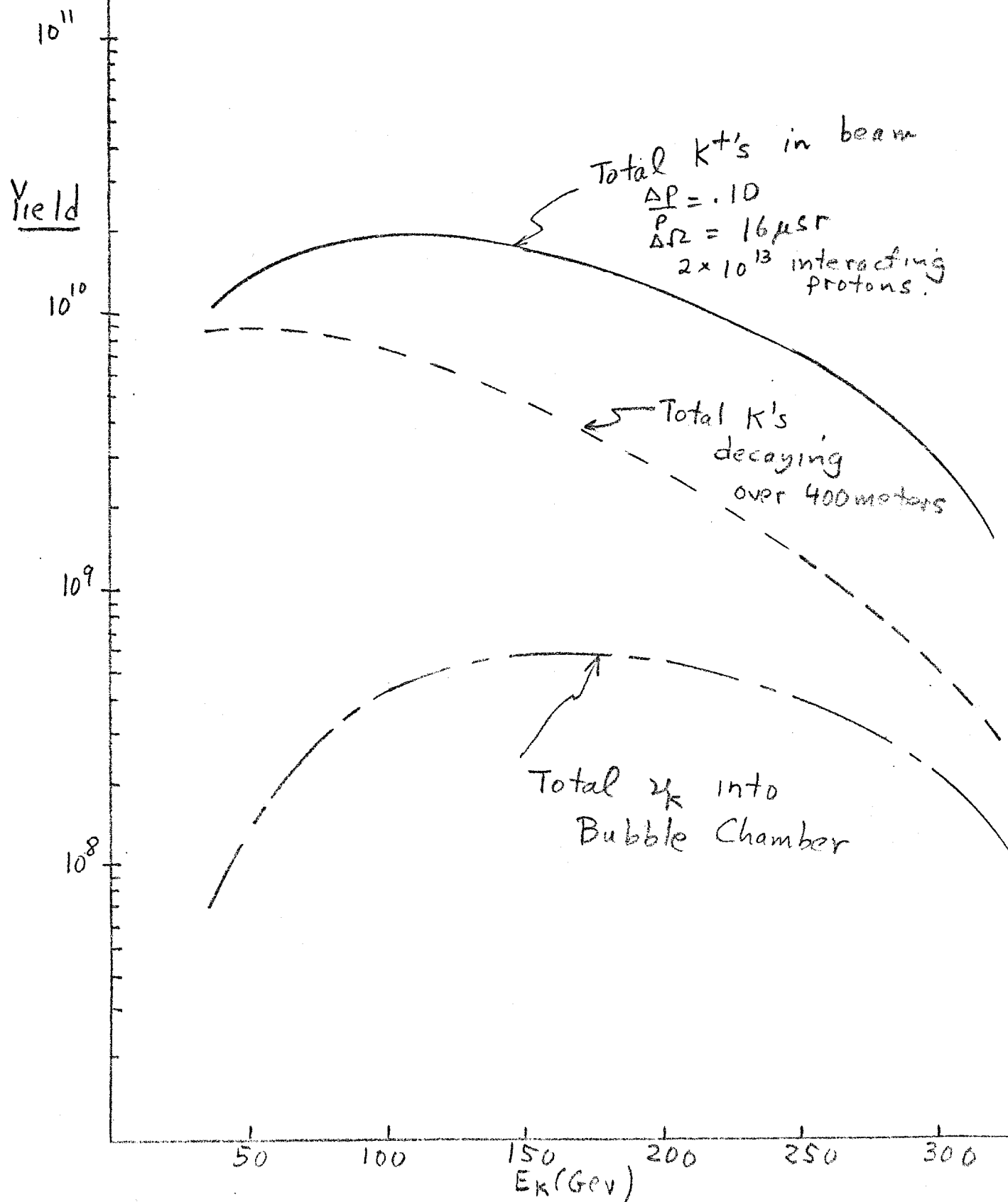


Figure 5

Kaon Neutrinos



$$\Delta\theta_{\text{horiz}} = \pm 0.38 \text{ mr}$$

$$\Delta\theta_{\text{vert}} = \pm 0.14 \text{ mr}$$

Neutrino Beam:

400 meter decay tunnel

1000 meter muon shield

3 meter diam. apparatus and

1.4 meter diam. apparatus (representing fiducial
area cut for better
resolution)

A description of a possible beam design for the target box was given in NAL Proposal No. 21 and we will not repeat it here. The number of pions/pulse sent down the decay tunnel is shown in Figure 4. The number of pions/pulse that decay to give neutrinos is also shown. Finally, those decay neutrinos that strike the sensitive volume of the bubble chamber is shown. Similarly the results for kaons is shown in Figure 5.

Figure 6 shows the number of neutrinos interacting in the bubble chamber per hour for the chamber full of liquid hydrogen and for neon. Note that there is roughly an event every 3 pulses in neon and every 50 pulses in hydrogen. Simultaneously point A (B or C) is measured for both pion and kaon neutrinos.

C. Resolutions

The use of the neutrinos from pion-decay, rather than those from K-decay, gives somewhat poorer resolution on the neutrino energy. Figure 7 shows the standard deviation on the neutrino energy ($30 < E_\nu < 80 \text{ GeV}$) as a function of energy. The standard deviation ranges $.07 < \sigma_\nu/p_\nu < .18$. At the lowest energies,

Figure 6

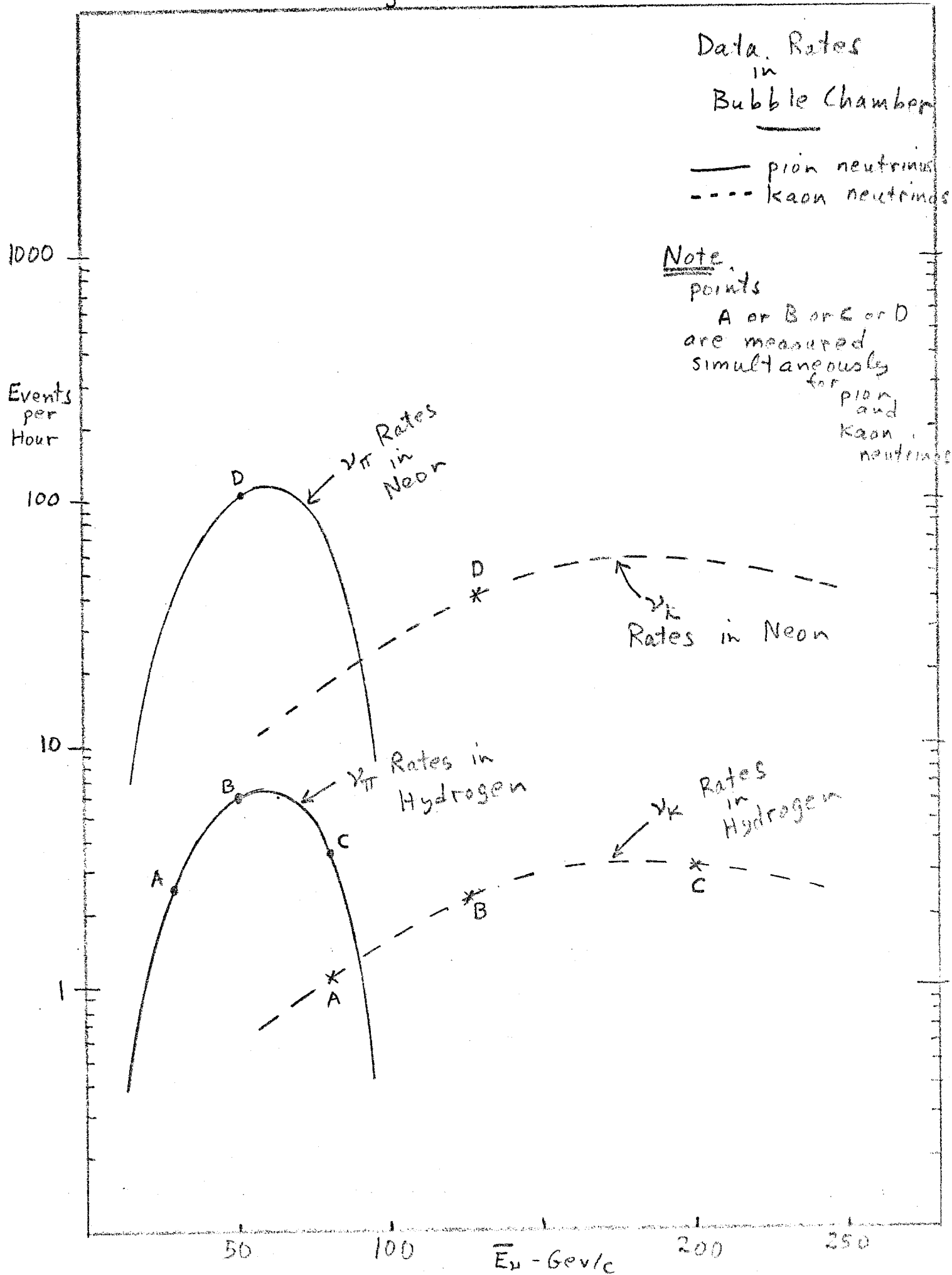
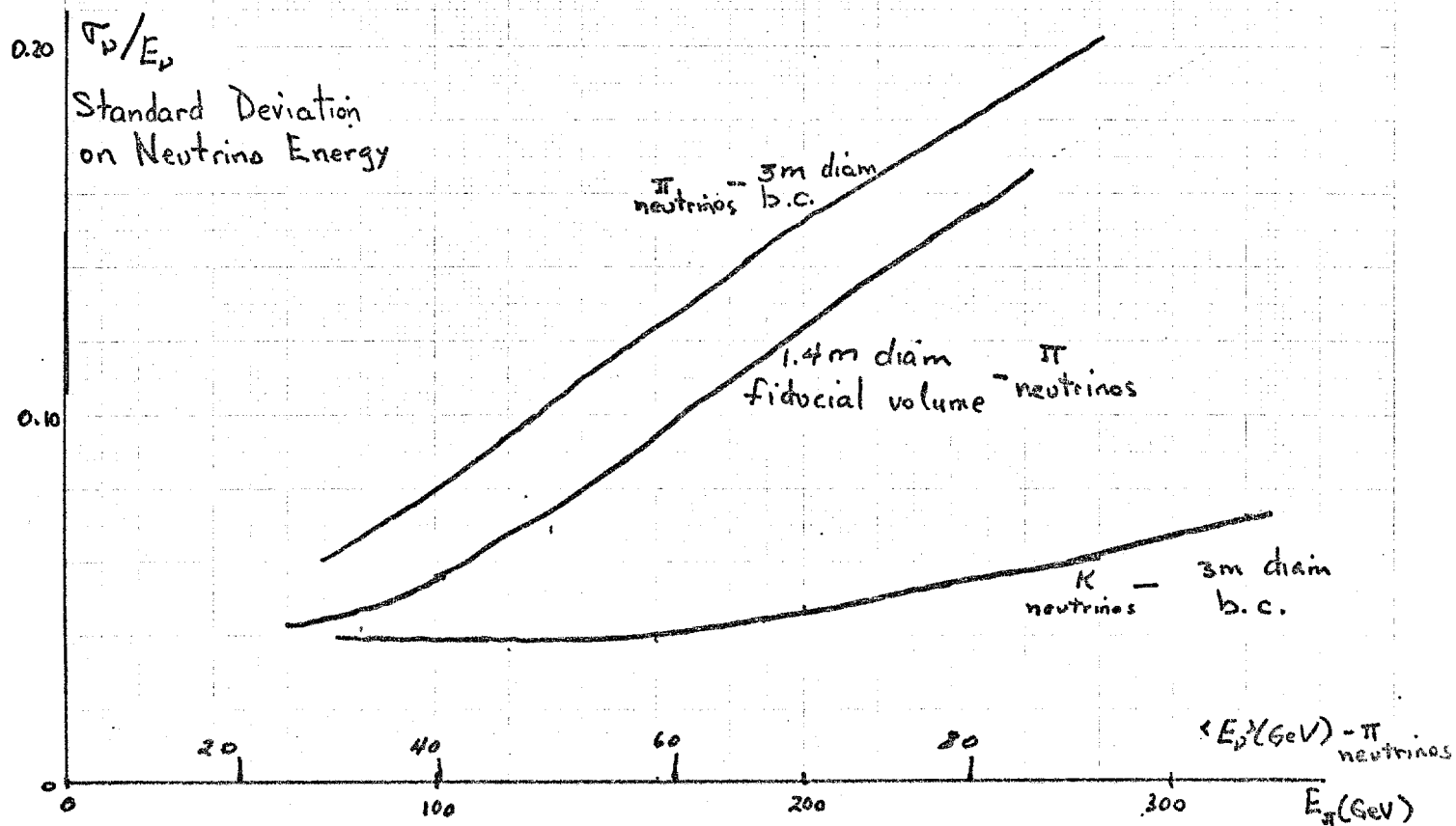
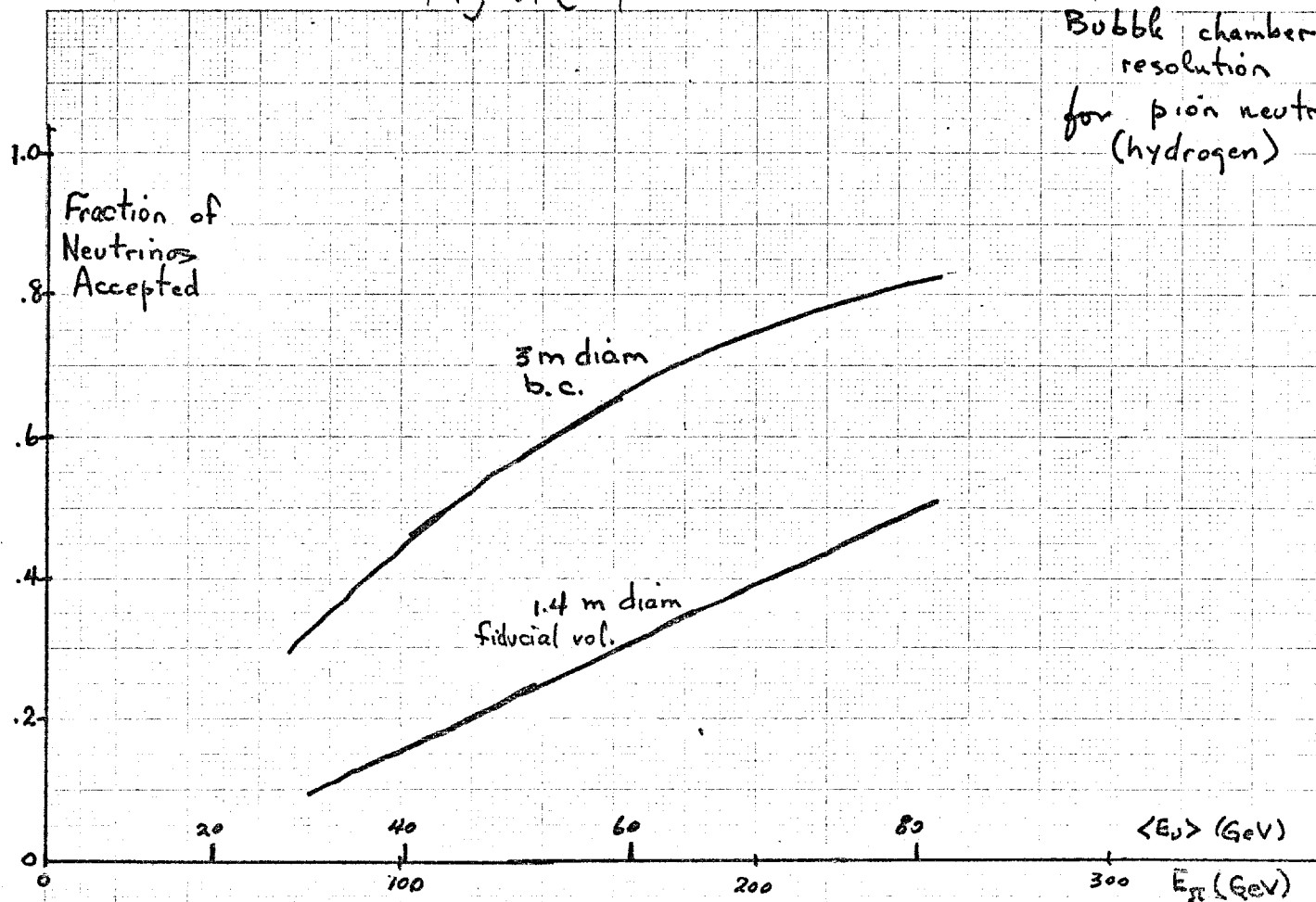


Figure 7

22 August (FS)

Bubble chamber
resolution
for pion neutrinos
(hydrogen)



this comes primarily from the finite ($\pm 5\%$) spread in pion energies in the hadron beam and at higher energies, the parallax of the decay region as viewed by points near the outside edge of the bubble chamber.

This latter error may be somewhat reduced by choosing a smaller fiducial volume inside the bubble chamber. For example, a 1.4 meter diameter fiducial volume gives a standard deviation at $E_\nu = 80$ GeV of $\sigma_\nu/p_\nu \approx 0.15$. Even though this fiducial volume contains less than one quarter the volume of hydrogen, the useful rate is 0.60 of the unrestricted fiducial volume. This is due to the sharp radial distribution of neutrinos in a monoenergetic beam.

Also of consequence is the resolution on kinematic parameters for deep inelastic scattering. The most commonly used are $y = \frac{E_\nu - E_\mu}{E_\nu}$ and $x = q^2/2M(E_\nu - E_\mu)$, where $q^2 = 2 E_\nu E_\mu (1 - \cos\theta)$. These cover the range $0 < x < 1$, $0 < y < 1$. Because we use the bubble chamber to measure the outgoing muon, the resolution on its momentum and angle should be quite good. In estimating the expected resolutions on these parameters, we have assumed

1. $\Delta E_\mu/E_\mu = .03$ is the standard deviation on the muon energy;
2. The resolution on E_ν is given by Figure 7 for the entire bubble chamber fiducial volume;
3. The resolution on θ is set by multiple scattering considerations and the standard deviation for point measurements in the bubble chamber is 0.33 mm.
4. The final hadron system, whose charged component

is measured to about $\pm 3\%$, is assumed to be measured in hydrogen to $\pm 20\%$ overall. This would be substantially improved in neon.

The multiple scattering error on θ means that there is a minimum detectable q^2 and x . The errors in energy measurement create an error in Δy and a fractional error in x .

These errors are functions of y only. Figure 8 shows typical resolutions as a function of y for $E_\nu = 50$ GeV.

It should be noted that the kaon neutrinos produce considerably smaller errors. Figure 7 shows the error in neutrino energy as a function of energy. The resolution on the kinematic parameters (x, y) is proportionately better.

D. External Equipment Required

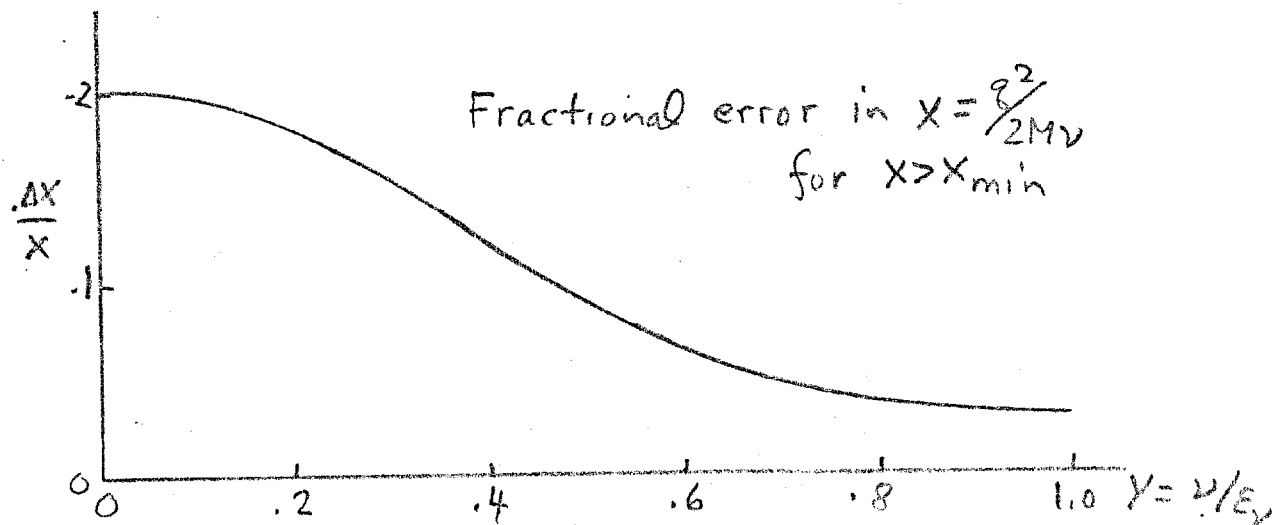
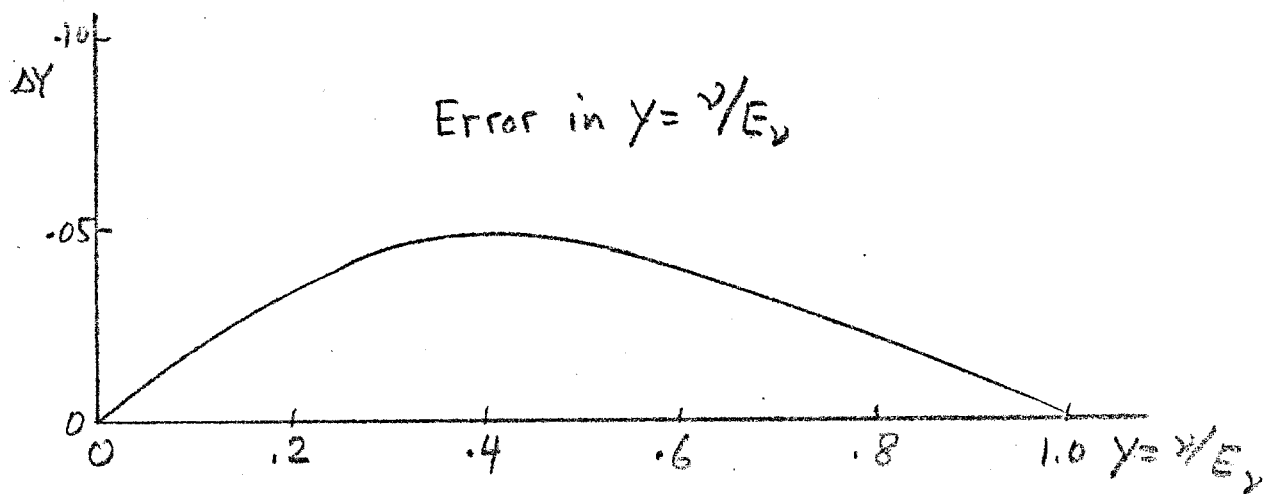
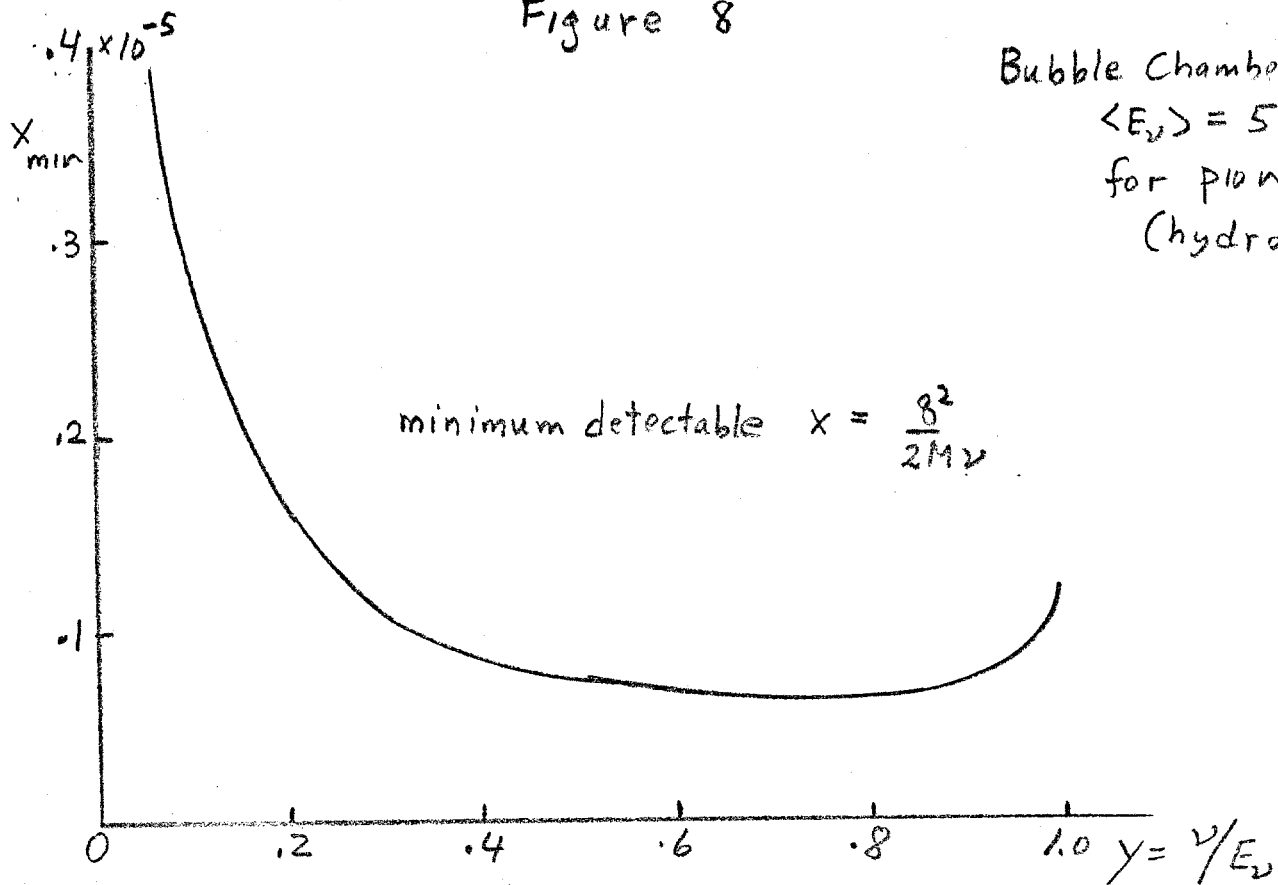
The experiment ^{may} require some information obtained external to the bubble chamber itself, but no modifications to the chamber.

For the neon running possibly nothing external is required. The rate is high enough to take a picture every expansion. Pion and kaon neutrinos can be separated by measuring the visible energy in the chamber and muons from the interaction could be distinguished from pions since the chamber is about six interaction lengths for pions.

For hydrogen or deuterium running certain external information may be valuable, depending on the kinematic

Figure 8

Bubble Chamber Resolution
 $\langle E_\nu \rangle = 50 \text{ GeV}$
 for pion neutrinos
 (hydrogen)



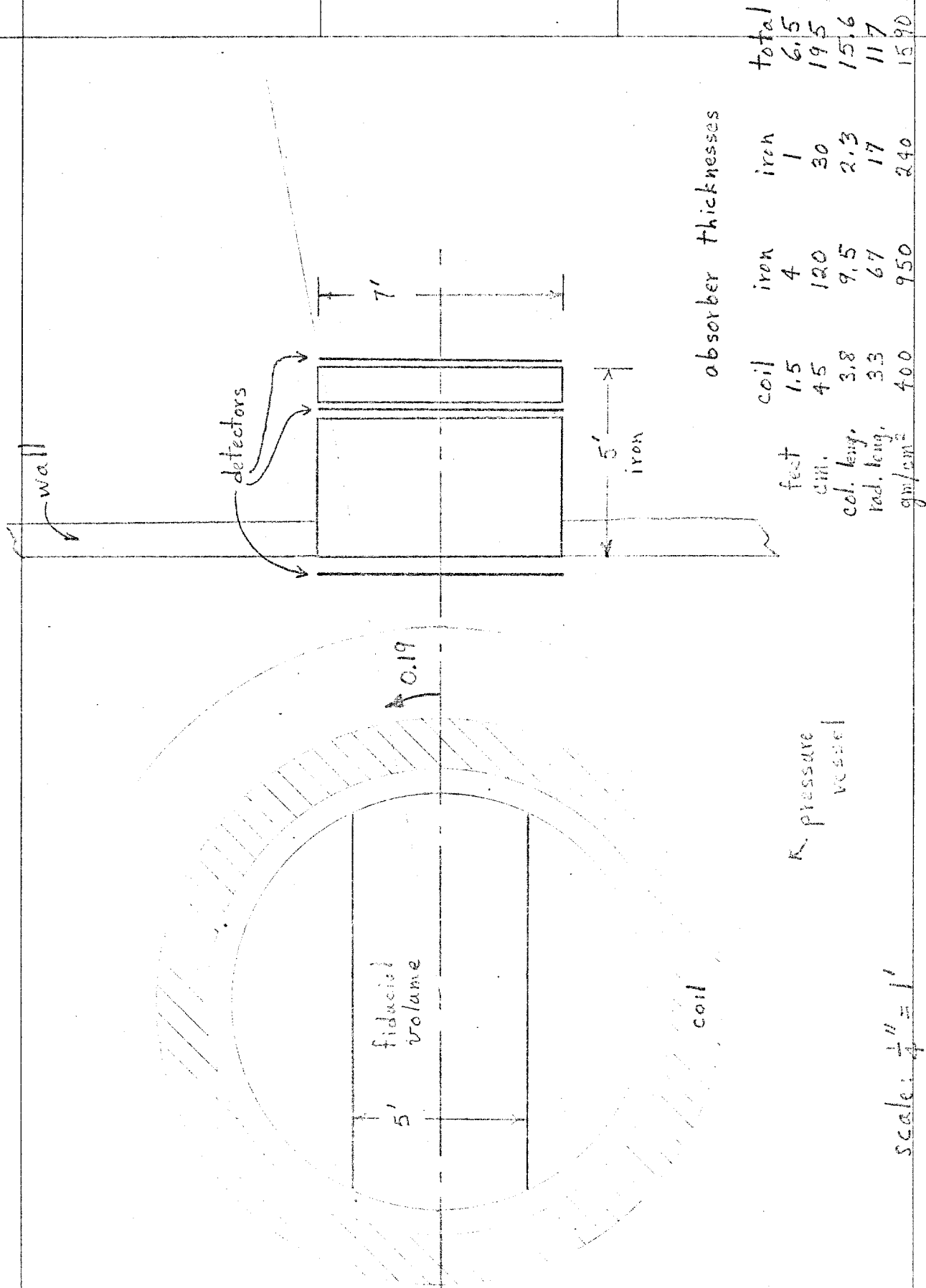
differences between π 's and μ 's. Figure 9 shows the configuration of an external muon identifier adequate for the needs of this experiment. It consists of a non-magnetic steel absorber 7' by 7' in area and 5' thick (12 collision lengths), three measuring stations as shown, and an anticoincidence counter in front of the bubble chamber (not shown). The absorber is thick enough that hadronic shower leakage through it is expected to be negligible, although this requires further investigation. Thus a muon is identified by penetration through the full absorber.

In Figure 10 we give the muon detection efficiency over the kinematics plane for two neutrino energies. To get a feeling for what these efficiency functions imply for gross event rates, the average efficiency for inelastic scattering is given below for two different form factor assumptions.

Average Efficiency of Muon Detector

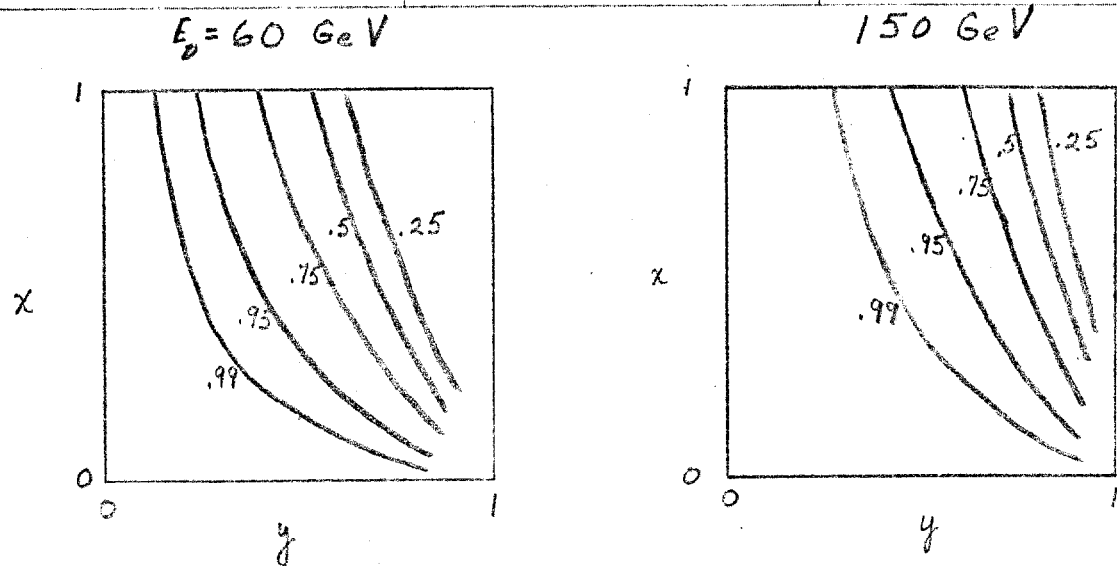
<u>$W_1 = W_3 = 0 \quad W_2 = \text{cnst}/\nu$</u>		<u>$W_3 = 0 \quad W_2 = \frac{2xm}{\nu} \quad W_1 = \frac{\text{cnst}}{\nu}$</u>	
60 GeV	86%		73%
150 GeV	95%		85%

The detectors (proportional chambers or scintillators) we need for this experiment covers only a small fraction of the area of the proposed general external muon identifier device for the bubble chamber. Furthermore, the low intensity of the monochromatic beam yields at most only a few interactions per pulse in the coils of the bubble chamber, whereas the proposed external muon identifier in a broad band beam would have to handle hundreds. A restacking



scale: $\frac{1}{4}'' = 1'$

Figure 9



Efficiency of External Muon Identifier

Figure 10

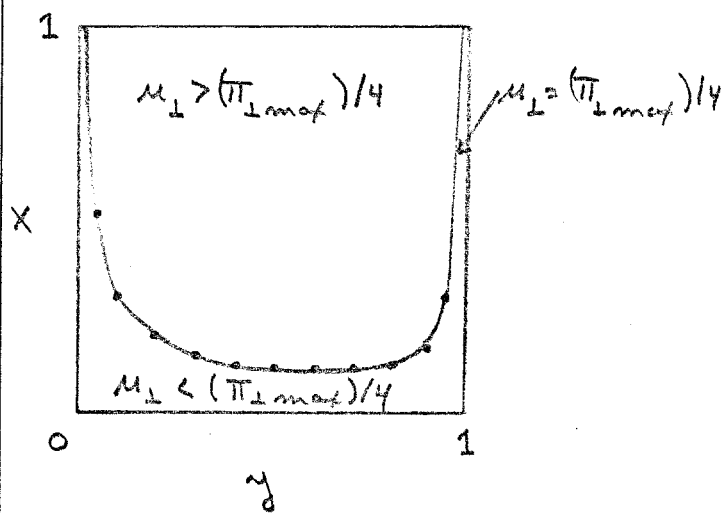


Figure 11

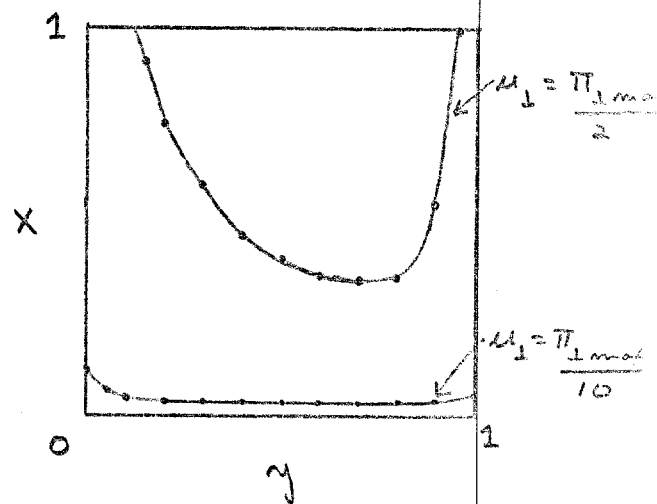


Figure 12

of the absorber of the general external muon identifier and a small fraction of its detector system fills the needs of this experiment.

E. Kinematic Muon Identification

The detection efficiency of the external muon identifier causes losses in the gross data rates which are acceptable. However, it seriously affects our ability to measure the form factor W_1 , whose coefficient in $\frac{d^2\sigma}{dx dy}$ is xy^2 and, to a lesser degree, vW_3 whose coefficient is $xy(1 - \frac{1}{2}y)$. It would be most desirable for these purposes to recover events which are missed by the external detector.

If the hadronic transverse momenta (relative to the momentum transfer vector \vec{q}) are only a small fraction of their maximum allowable value ($\frac{\sqrt{mE_{\nu}y(1-x)}}{2}$) then it is possible to distinguish the muon from the hadrons in each event with a high probability over most of the kinematic range. In purely hadronic reaction, we know that the transverse momenta (relative to the incident hadron direction) have a severely restricted distribution whose width is independent of energy. In hadronic reactions initiated by a current this distribution is, of course, unknown but all models so far proposed give transverse momenta that are considerably less than the maximum value that is allowed kinematically.

Crudely speaking, if a pion is incorrectly assigned to be the muon, then the real muon may have a transverse momentum much larger than one might have expected from a pion. Whether or not the muon has a large enough transverse momentum to

signal a misidentification depends on its value of x and y . Those values of x and y which would give the muon a transverse momentum (μ_{\perp}) greater than one quarter the maximum value that is kinematically allowed for a pion ($\pi_{\perp \max}$) is shown in Fig. 11. Other illustrative examples are given in Fig. 12. The curves are independent of the neutrino energy.

The essential point is that if the transverse momentum of the pions are not too large, the region of the x - y plot where the external muon identifier is inefficient is just the region where the muon may be identified kinematically. If the pion transverse momenta are small enough, the external muon identifier may not be required at all. We hope to resolve the question of the necessity of an external muon identifier by obtaining a crude measurement of the pion transverse momenta in Experiment #21.

F. Experimental Needs

- 1) Monoenergetic beam.
- 2) Bubble chamber.
- 3) Analysis facilities.
- 4) External equipment to be determined.

Measuring facilities will be available at Cal-Tech to analyze the film. A POLLY film digitizer, which will be operational during 1971, is presently being constructed.

F. Conclusions

We propose here an exposure using the NAL 30m³ bubble chamber. One unique feature of the experiment is the use of a momentum defined neutrino beam. This helps simplify the "hybrid" nature of studying high energy neutrino collisions, and makes the experiment easily and reliably interpretable. Some

simple external apparatus may still be needed to eliminate certain ambiguities.

A summary of the number of events expected in an experiment of the size proposed is given in the Table below.

Incident Particle	Momentum (GeV)		Liquid in B.C.	Expansions	Events **	
	ν_π	ν_k			ν_π	ν_k
ν	30	80	Hydrogen	70K	500	165
	50	125		40K	620	310
	80	200		70K	580	550
$\bar{\nu}^*$	50			70K	600	-
ν	50	125	Deuterium	90K	2800	1400
$\bar{\nu}^*$	50			160K	2500	-
ν	50	125	Neon	250K	71,000	35,000

* Assumes $\sigma_\nu = \sigma_{\bar{\nu}}$

** Assumes $\sigma = .6 \cdot 10^{-38} \times E_\nu$

REFERENCES

1. Bjorken and Paschos, SLAC Pub. 678 (1969).
2. Budagov, et.al, Phys. Letters 30B, 364 (1969).
3. L. M. Lederman, Proceedings of the International School of Physics "Enrico Fermi" XXXII (Academic Press, 1964), p. 186.
4. D. O. Caldwell, et.al., Phys. Rev. Letters 23, 1256 (1969).
5. S. Adler, Phys. Rev. 135, B963 (1964).
6. J. Lovseth and J. Froyland, Il Nuovo Cimento 53, 1 (1968).
7. K. Borer, et.al., Phys. Letters 30B, 572 (1969) and M. Holder, Lettere al Nuovo Cimento 3, 445 (1970).
8. D. J. Gross and C. H. Llewellyn Smith, Nuclear Physics B17, 277 (1970) and Reference 1.
9. S. D. Drell, et.al., Phys. Rev. Letters 22, 744 (1969) and SLAC pub.'s 606, 645, and 685.
10. See review by C. H. Llewellyn Smith, Th. 1188-CERN (1970).
11. H. Harari, Phys. Rev. Letters 22, 1078 (1969) and Phys. Rev. Letters 24, 286 (1970).
12. C. Jarlskog, Nuclear Physics 75, 659 (1966).
13. D. Fryberger, Phys. Rev. 166, 1379 (1968).
14. C. Jarlskog, University of Lund preprint (April 1970).